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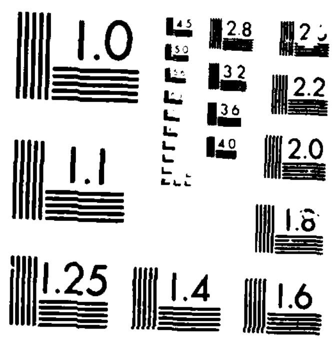
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Report is an assessment of current and possible applications of net shape technologies by the Air Force, including: precision forging of alloys, powder metallurgy, structural ceramics, superplastic forming, diffusion bonding, vapor deposited coatings, etc.; and composites, including organic matrix composites, metal matrix composites, ceramic and carbon matrix composites in the manufacture of aircraft components. Report includes road maps of research and development efforts in performance and manufacturing technologies and resource allocation.

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Net Shape Technology in Aerospace Structures

Volume I

Committee on Net Shape Technology
in Aerospace Structures
Air Force Studies Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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STATEMENT OF TASK

The Committee on Net Shape Technology in Aerospace Structures will conduct a workshop on net shape technology to assess whether the development of material and manufacturing technology in net shape fabrication processes is progressing to meet future requirements. Emerging processing technologies will be addressed if the net shape technology workshop indicates such a requirement. This would be the second workshop. A third workshop will be considered following the second workshop in the area of composites.

The committee will consider technology advances to support improved performance requirements. The study should identify the hurdles in manufacturing technology to fabricate net shape products that will meet improved performance levels with enhanced levels of productivity with reduction in overall cost.

The final report to Air Force Systems Command should provide a road map of research and development efforts in performance and manufacturing technologies and resource allocation.

PREFACE

In the spring of 1984 the Commander, Air Force Systems Command, requested the Air Force Studies Board to assess the manufacturing technology of net and near net shape components for Air Force Systems. A committee was organized under the chairmanship of Dr. Morris A. Steinberg, Vice President for Science, Lockheed Corporation. The committee first met in July 1984 to outline a course of action for this study.

The committee held three workshops: Workshop 1, Precision Forgings in Aerospace Structures; Workshop 2, Emerging Net Shape Technologies; and Workshop 3, Composites.

This report is in four volumes. Volume I is the committee's assessment of the state of net shape technology for aerospace applications based on briefings and discussion at the workshops. It includes recommendations and road maps for research and development needed to properly advance the use of net shape technology, and represents the position of the National Research Council. Papers presented by invited speakers at the workshops appear in Volume II (precision forging), Volume III (emerging technologies), and Volume IV (composites). The opinions expressed in these papers are solely those of the respective authors.

CONTENTS

Volume I

EXECUTIVE SUMMARY

Net shape technology concerns fabrication of parts directly to final dimensions. It promises significant savings in the manufacture of high-performance aerospace structures, savings that are mandatory in today's economic climate. To help realize these potential benefits, the Air Force Systems Command asked the Air Force Studies Board (AFSB) of the National Research Council to assess the manufacturing technology of net and near net shape parts. The board was to identify needs that must be met to satisfy the demands of emerging weapons systems.

The AFSB Committee on Net Shape Technology in Aerospace Structures assessed the technology in three areas: precision forging, emerging net shape technologies, and composite materials. The committee developed 60 recommendations and devised road maps for the work needed to resolve the technical and institutional problems identified. The recommendations and road maps appear in this volume of the report.* This Executive Summary includes only the recommendations of broadest import.

PRECISION FORGING

Precision forging is used mainly with aluminum alloys, but also with titanium alloys, nickel base superalloys, and steels. The process yields parts that require little or no machining and are uniformly strong. The dies cost more than conventional forging dies, but the difference may be offset by fewer than a dozen parts because of savings in machining costs. Precision forging today is used primarily to reduce costs by reducing the materials and machining needed to attain net shape. The benefits it offers in the properties of parts are not yet a major factor in its selection over competing metal-forming processes.

Savings Achievable

The savings achievable by precision forging depend on several factors, including the material and geometry of the part. As an indicator, however, when more than 200 parts are to be made, precision forging of aluminum alloys may reduce cost as much as 90% compared to parts machined from stock.

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*The report includes formal briefings at three workshops organized by the committee. These appear in Volume II (Precision Forgings in Aerospace Structures), Volume III (Emerging Net Shape Technologies), and Volume IV (Future Composite Manufacturing Technology).

Forging Technology

Precision forging of aluminum alloys is technologically well established, although highly empirical. Precision forging of titanium alloys is more difficult and less well developed, although used regularly on a production basis. Wider use of the process with alloys of both metals is inhibited by technical problems that include limitations on the sizes of parts that can be made, particularly from titanium.

The Forging Industry

In addition to technical difficulties, the nature of the precision forging industry itself inhibits wider use of the process. Of the approximately 200 forging shops in this country, only about 20 supply precision forged parts for the multibillion dollar aerospace industry. Precision forging is highly capital intensive. The companies involved tend to be relatively small, with aging equipment prone to breakdown. Studies of the industry have revealed many bottlenecks. They include inordinate use of critical equipment for die tryout and proofing, outdated methods of die design and fabrication, and inadequate methods for materials handling and production control.

The state of the art in designing and producing forging dies and forgings involves computer aided design and manufacturing (CAD/CAM) and numerically controlled (NC) machining. These technologies are not yet widely used for several reasons: some techniques are not fully developed, the costs of introducing the technologies are relatively high, especially for small companies, and qualified manpower is in short supply.

The precision forging industry on the whole seems ill-equipped to cope with a surge in civilian aerospace demand or a mobilization effort. As matters now stand, the industry's entire capacity in CAD/CAM and NC machining would be tied up by one commercial aircraft program released for production with 1,200 precision forging configurations.

The large aerospace companies are generally adapting the new technologies to their particular needs. The Air Force is pursuing an advanced computer aided engineering (CAE) system, including a generic computer program (ALPID) that can be applied to any of the common metalworking processes. Nevertheless, diffusion of advanced technologies through the precision forging industry faces serious barriers, not the least of which is the size of the necessary capital investment.

Large Press Capability

The committee considered the desirability of acquiring a large forging press capability in the United States. The question has been debated for almost 20 years. Significant studies have been made and reported, but no action has occurred at any level. We recognize the apparent need for improved capability for large near net or net shape forgings, with plan view areas greatly in excess of 600 sq. in. We further recognize that significant improvements in control of forging parameters have been made in recent years. With this understanding, we believe that a second generation of large forging presses, incorporating the latest technology in microcomputer control, ALPID computer programming, etc., warrants consideration by the Air Force.

Recommendations - Forging

The needs that follow are the most pervasive of the 24 identified by the committee in precision forging. We recommend that all of the 24 needs be met to insure the existence of a sound industrial base in this important technology.

- Rapid further development and field application of the Air Force's ALPID program for CAD/CAM in metalworking and completion on schedule of the Manufacturing Science Program in Die Design and Manufacturing.

- Incentives for encouraging modernization and expansion of firms producing precision forgings by:
  - Adoption of CAD/CAM.
  - *Improved use of equipment.*
  - Improvement of the forging process.
  - Addition of capital equipment, including inspection equipment.
  - Financial partnership of prime contractors and subcontractors to increase investment and profitability.
  - Provision of R & D funds directly to small forgers to permit them to improve the use of existing equipment and improve the quality of their products.

- An organized effort by the aerospace industry and the Air Force, in cooperation with the Forging Industry Association, to develop training programs for precision forging die design and manufacture, including NC programming and machining. Such programs would include simple methods and computer assisted techniques.

- Encouragement and funding of basic and applied research in net shape forging, including: prediction of metal flow; distribution of stress, strain, and temperature in the workpiece; and load and energy requirements during deformation.

- Expanded activities on the finite element and other methods to develop codes adaptable to analysis of precision forging, die design, lubricant selection, etc., and to remove existing barriers to use of CAD/CAM.

- Encouragement of funding of additional research on methods for improving the properties of existing die materials and developing new die materials.

EMERGING NET SHAPE TECHNOLOGIES

Emerging net shape technologies that we examined were powder metallurgy, structural ceramics, powder consolidation processes, superplastic forming, diffusion bonding, and vapor deposited coatings. These technologies generally are not new, but are still emerging as ways to make high-performance aerospace parts.

Powder Metallurgy

It has become possible in the past few years to make high-performance parts from rapidly solidified powders (RSP) using powder metallurgy (PM) techniques. The powders are densified and extruded into billets that serve as stock for precision forging. The primary aerospace uses of this approach today are superalloy turbine and compressor disks for aircraft jet engines.

A general problem with PM superalloys is contamination by ceramic inclusions and trapped gas voids during powder production. Potential solutions include better melt-refining processes and ceramicless powder production facilities.

Developments in aluminum powder metallurgy include alloys intended in part to replace titanium in uses where the required heat resistance lies between that of conventional high-strength aluminum and titanium. A major need is a consistent process, under real-time control, for making RSP aluminum alloy.

Consolidation of Metal Powders

Consolidation processes for metal powders include hot isostatic pressing (HIP) and consolidation by atmospheric pressure (CAP), a proprietary process. HIP is used to press metal powders into billets for subsequent operations such as extrusion and forging. It is also used to make near net shape parts, including some aerospace parts, that are used as-HIPed except for machining. The future of as-HIPed technology for aerospace parts is not clear because too little is known of the structure and behavior of individual metal particles to support firm conclusions about the potential of the technology.

CAP is used to compact metal powders into preforms for further processing and can produce near net shapes. It is used commercially only for high speed tool steels, but is being evaluated for making disks for gas turbines.

Structural Ceramics

Ceramics are unusually resistant to heat, and the newer ones, such as silicon carbide and nitride, are much stronger than traditional ceramics. These characteristics have spurred considerable research and development on structural ceramic parts for use in extreme environments, such as gas turbines.

Most ceramic parts can be made by several processing routes. Generally they involve forming a powder into the desired shape, drying, and sintering. Parts must be made as close as possible to net shape -- machining the sintered material is costly and can reduce the strength of a ceramic part by damaging its surface. All forming processes for structural ceramics require further development to improve quality, reproducibility, reliability, productivity, and cost.

Superplastic Forming/Diffusion Bonding

Superplastic forming depends on the ability of a metal, under certain conditions of temperature and microstructure, to elongate uniformly by several hundred percent without failing. This property permits metals to be formed into complex parts using methods not previously possible. In airframe and engine components in the U.S., superplastic forming thus far is used mainly with titanium sheet.

Diffusion bonding involves intimate contact between parts at elevated temperature and pressure and diffusion of atoms across the interface. The combination of superplastic forming and diffusion bonding (SPF/DB) is well suited to fabrication of titanium alloys. Parts can be formed and bonded by SPF/DB in sequential steps in the same equipment.

Vapor Deposited Coatings

Aerospace uses of net shape parts may impose demands on materials that can be met only by resorting to protective or functional coatings. Airfoils in aircraft gas turbines, for example, are protected against oxidation/corrosion by MCrAlY alloy coatings (M can be nickel, cobalt, or iron). The performance goals of the next generation of military gas turbine engines will call for significant improvements in coatings. The requirements will include erosion protection for titanium alloys, thermal protection for nickel base superalloys, and thermal/oxidation protection for carbon-carbon composites.

The coatings of interest generally are deposited by physical or chemical vapor deposition processes. These processes tend to be based on experience rather than detailed scientific knowledge, which handicaps scale-up and adaptation of processes to new materials. Theories of adhesion, for example, do not adequately explain the behavior of some coating-substrate combinations.

Recommendations -- Emerging Technologies

We recommend that the 16 needs identified in emerging technologies be acted on to speed sound application of the technologies to manufacture of net shape aerospace parts. The needs of highest priority are specified below.

- Closed-loop control of processes for producing rapidly solidified metal powders. This effort will require the development of quantitative process models, sensors for critical variables, and process controls. It will require that relationships be established between process variables and the quality and size distribution of powders. It may require modification of atomization processes to permit continuous operation.

- Accelerated R & D on improved melting methods and ceramicless atomization for superalloy powders to support detailed design of a production system incorporating these features.

- Development of process modeling and control of powder consolidation and improvement of microstructural control of powder-metal parts.

- Scale-up of laboratory fabrication processes for structural ceramics to the commercial level. Accelerated development of quantitative understanding of structural ceramic forming processes, the sensors and controls needed to place these processes under closed-loop control, and the associated data bases.

- A wider range of domestically produced ceramic raw materials, including high-quality powders and reinforcing particles and fibers.

- Further development of the scientific basis of deposition processes, and development of process models, sensors, and controls required for real-time control of such processes.

FUTURE COMPOSITE MANUFACTURING TECHNOLOGY

Use of composites in U.S. military aircraft is dominated by thermosetting organic matrix materials, mainly epoxy polymers reinforced with graphite fibers. Composites of this type comprise as much as 28% of aircraft structural weight (on the AV-8B). Metal and ceramic matrix composites are less developed than organic matrix materials and as yet have relatively few aerospace applications.

Composites are expected to comprise 40-50% of structural weight on the Advanced Tactical Fighter. This and comparable aircraft will require improved composites for both airframes and engines. Organic and metal matrix composites are candidates for both, and ceramic matrix materials are candidates for engines. Applications of aerospace structural materials and current capabilities and goals for composites are shown in Figure 1. As the figure shows, advanced aerospace vehicles of the future will require materials that can withstand temperatures approaching 5000 ° F. The structures of interest will include large transports, subsonic vehicles, supersonic fighters, high-performance supersonic fighters, rotorcraft, missiles, and engines.

Thermoset Organic Matrix Composites

Graphite/epoxy composites are well suited to aircraft applications, but have shortcomings. They are brittle, their sensitivity to moisture limits them to service temperatures below 260 ° F, and processing is slow and costly. The prepreg used to make graphite epoxy parts is tape or cloth impregnated with partly cured resin; it is converted to parts by stacking precut plies and curing. The problems with prepreg are associated with its quality, reproducibility, variations in thickness, and physical defects. These problems raise costs and hamper the automation needed for mass production of parts. A major immediate need is close-tolerance prepreg manufactured to uniform specifications. Achieving the needed improvements in quality will require more thorough characterization and standardization of starting materials than is now common, and automated process control and adjustment.

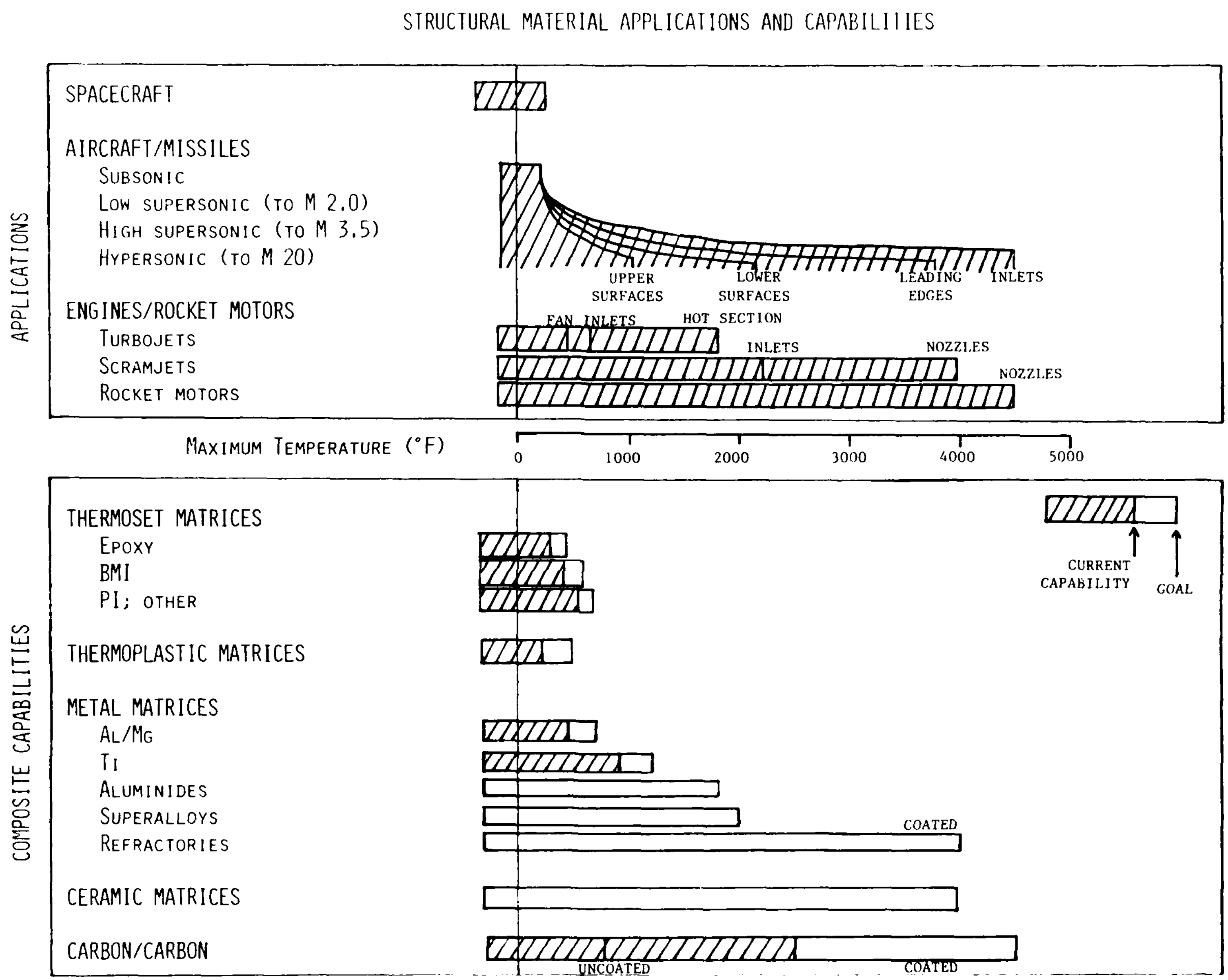

FIGURE 1 STRUCTURAL MATERIAL APPLICATIONS AND CAPABILITIES

The cost of thermoset resin composite parts might be reduced by using advanced curing methods, such as nonautoclave curing (under vacuum in an oven), coldwall autoclave curing, pultrusion, radio frequency (RF) curing, elastic reservoir molding (a compression molding process), and electron beam irradiation. Some such methods are in limited use or are used in other fields. Development of new curing techniques is not particularly costly and probably would best be funded by relatively small contracts.

Tooling systems must be adapted to the use of CAD/CAM. Metal tools are durable and conduct heat well, but suffer from the mismatched thermal expansions of tools and parts. Composite tools do not have the thermal expansion problem, but suffer from low thermal conductivity, poor durability, and high maintenance and repair costs. Limited work on tooling systems and materials is under way.

Thermoplastic Organic Matrix Composites

Much effort is under way to develop aerospace composites based on thermoplastic resins, which promise greater toughness and cheaper fabrication than thermosets. The toughness would permit fuller exploitation of the properties of graphite fibers now available. Since the fully polymerized flat sheet can be thermoformed to shape, fabrication should be less costly.

Thermoplastics cost more than thermosets, and unforeseen deficiencies, such as inadequate solvent resistance in some cases, have slowed their progress. Their fatigue and creep behavior, especially at high temperature, remain uncertain. Candidate resin systems are multiplying, which hampers the development of design and manufacturing data. Basic design data are woefully lacking in all systems. No composite parts based on thermoplastics are yet flying.

Low Cost Production of Organic Matrix Components

Low cost methods of making organic matrix composite parts are urgently needed. Approaches include automated fabrication, new concepts in tooling and curing, better methods of joining, and improved methods of nondestructive evaluation (NDE) of parts. Automated fabrication techniques now emerging were developed largely for parts designed originally for manual or semiautomated techniques, but second generation composite structures will be designed for fabrication by these facilities. Thus design-manufacturing integration is a developing technology. Its progress should be coordinated and closely monitored because of the real danger that each manufacturer might otherwise develop unique engineering capabilities and facilities. Such an outcome would seriously impede surge capabilities, possibilities of teaming, and acquisition of second sources.

Development of integrated technology for design, fabrication, and tooling for filament-wound primary structures is needed. Pultrusion is used to make shapes of constant cross-section continuously by pulling resin impregnated reinforcing material through a heated die. Pultrusions are relatively affordable, but can be made only in straight sections. Future uses could include stiffeners for wing or fuselage covers of large transport aircraft, shells of missile structures, or tubular parts of large space structures. Injection molding involves injecting liquid resin into a closed die containing a stitched preform of reinforcement material. The process is limited to detail parts, but is very effective for parts of highly curved or complex shape.

Several methods of automated fabrication of organic matrix composites are being developed and used. They range from ply lamination through assembly and quality assurance. A specific need is progress in sensor and video camera technology for continually assuring that all parts of the fabrication system are operating properly.

Emphasis on quality assurance of organic matrix composite parts is shifting to continuous monitoring and inspection, from the earliest design phase through the complete manufacturing process. Use of automated manufacture and NDE makes delay in the disposition of rejected parts a serious problem that would be eased greatly by the development of guidelines for assessing and repairing manufacturing defects on the basis of statistically meaningful test data.

Additional issues concern standardization of materials and the supply of skilled manpower. Urgently needed are standardized classes of composite systems with extensive data bases of physical properties and design allowables. The manpower problem is the result of the absence of a comprehensive approach to training people in composites manufacturing and processing.

Metal Matrix Composites

Metal matrix composites, although at a much earlier stage of development than organic matrix materials, promise very desirable characteristics: superior high temperature properties, low coefficients of thermal expansion, good survivability, tailorable physical and mechanical properties, and adaptability to net shape manufacturing. The high cost of materials and labor-intensive fabrication methods impede their use. Many suppliers are small companies that have limited resources and need increased development funding.

Process development for metal matrix composites should be focused on automated methods to make net shape parts at low cost. NDE of parts is critical, and new ways are needed to inhibit degradation of reinforcing fibers during the high temperature processing cycle. Establishment of a small technical effort to follow commercial developments in these materials would be worthwhile.

Ceramic and Carbon Matrix Composites

Ceramic matrix composites are at an even earlier stage than metal matrix materials, with the exception of carbon/carbon composites being developed for jet engine parts. Ceramic matrix materials nevertheless have the best high temperature potential of all composites, and lower radar detectability.

A general need for ceramic matrix composites is development of materials and processes. Those available are limited and far from mature. They require work in several areas of basic science, including the micromechanics of toughening and strengthening brittle materials. Also required are better methods of NDE to determine degradation of fibers by reaction with the matrix.

Experimental gas turbine parts are being made in France using a silicon carbide matrix and carbon or silicon carbide fibers. Test parts with glass and glass ceramic matrices have been made in the USA for gas turbines, diesel engines, and other applications. Development of near term uses for ceramic matrix composites should be focused on secondary structures, such as high temperature radomes, and shifted to more critical structures as the technology matures. The materials have good potential for electronic and microwave packaging, and cutting tools are being made commercially of alumina reinforced with silicon carbide whiskers.

Recommendations -- Composites

To achieve the required improvement in manufacture of high quality, affordable net shape composite aerospace parts, we recommend that action be taken on the following needs:

Materials

- Improve physical and chemical consistency and quality of thermoset resin prepreg material. Establish a National Center and a Military Handbook to set uniform specifications and standards for qualified materials.
- Increase R & D funding of metal, ceramic, and carbon matrix components. Monitor associated world-wide commercial activities and development.

Manufacturing

- Coordinate organic matrix composites and computer-integrated design manufacturing quality control to take full advantage of automated manufacturing. Develop an associated costing method and data base.
- Continue development of associated manufacturing technology such as pultrusion processes and injection molding for organic matrix composites, and affordable net shape processes for metal and ceramic matrix composite parts.
- Develop special inexpensive fasteners for composites.
- Sponsor university positions in composite manufacturing.

Nondestructive Evaluation (NDE)

- Develop NDE procedures and sensors for all composites manufacturing operations including bonded joints and assemblies.

Repair

- Develop battle damage repair procedures using thermoplastic materials or adhesives that cure rapidly at room temperature. Generate repair information for automated battle damage assessment.

Applications

- Support application studies that are performed by teams of prime contractors, subcontractors, and materials and equipment suppliers to develop the technological capabilities needed to transfer the technology throughout industry.
- Provide small amounts (\$500,000-\$800,000) of Air Force discretionary funds for rapid development of critical technological needs.

Conclusion

We concluded that technology for producing net shapes is not advancing fast enough to meet Air Force needs. The investment strategy we recommend for improving net shape technology is described in road maps for research and development and related efforts. They show in coordinated form the tasks to be pursued and the years of effort likely to be required. As noted at the outset of this summary, the road maps and all of the recommendations appear in this volume of the report.

We wish to emphasize, finally, that swift progress in net shape technology promises considerably more than affordable, high-performance parts for Air Force and other military vehicles. The technology also can contribute significantly to the nation's international competitiveness in commercial aerospace vehicles.

INTRODUCTION

Net shape technology - fabrication of parts directly to final dimensions - promises significant economies in the manufacture of high-performance aerospace structures. With this in mind, the Air Force Systems Command asked the Air Force Studies Board of the National Research Council to undertake the study reported here. The immediate purpose was to assess the manufacturing technology of net and near net shape parts. More broadly, the study was designed to help the Air Force answer two questions:

- Is net shape technology advancing fast enough to meet the demands of emerging weapons systems?
- What investment strategy should the Air Force pursue to maximize procurement of weapons systems at reasonable cost without loss in quality?

To conduct the study, the Air Force Studies Board appointed a Committee on Net Shape Technology in Aerospace Structures. The committee sought the broad range of information it needed primarily by means of three workshops.*

This volume is the first of four that make up the report. It combines a synthesis of the briefings and discussions at the workshops with our assessment of the state of net shape technology for aerospace applications. The briefers' formal presentations appear in Volume II (precision forgings), Volume III (emerging technologies), and Volume IV (composites).

Sections 1-3 of this volume include sets of technical and institutional needs that we believe must be met to realize the full potential of net shape technology. They also include road maps of the research and development required in specific areas of the technology. Appendices A, B, and C list the participants in the workshops. Appendix D is a list of acronyms.

BACKGROUND

The metalworking industry has made great strides in the accuracy, complexity, and producibility of shapes with traditional fabrication processes. Improved metallurgical alloys and the ability to machine to very high tolerances have yielded parts with outstanding properties for use in high performance aerospace vehicles. Recent advances in cutting tool materials (e.g., coating technology) have permitted higher metal removal rates and decreased machining cost of this function in manufacturing. New applications of computer numerical control (CNC) and direct numerical control to machine tools permits quality to be improved by mechanizing repetitive steps in the machining process. Automation in machine tool setup and fabrication centers has increased productivity.

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*Workshop schedule: Precision Forgings in Aerospace Structures, Oxnard, California, December 3-5, 1984; Emerging Net Shape Technologies for Aerospace Structures, Santa Barbara, California, March 27-29, 1985; Future Composite Manufacturing Technology, Gaithersburg, Maryland, September 9-12, 1985.

Implementation of various technologies developed under the Air Force Integrated Computer Aided Manufacturing program can reduce costs and improve productivity in the transition from design to production. Several concepts in the design of parts and selection of materials have yielded production methods that may have major impact on manufacturing. Besides the choice of materials (aluminum, titanium, composites, etc.) and processes (casting, forging, machining, and powder metallurgy techniques), designs can now be realized with the use of CAM methods.

It has been suggested that the development of processes for fabricating parts directly to net shape could produce important, cost reducing substitutes for conventional fabrication practices. Improvements in the production of hardware for weapons systems generally have lagged behind the introduction of new technology in the hardware itself. Today's economic environment, however, demands more efficient use of our production dollars. Thus development of more economical manufacturing technology for aerospace hardware is mandatory. Whether considering a new material, a new design, or a new production method, one of the most cost-effective processes that can be evaluated for making high performance components is precision, net shape technology.

In accord with our assigned task, we focused on the plans and requirements of the Air Force. We emphasize, however, that progress in net shape technology can also contribute significantly to the nation's international competitiveness in commercial aerospace vehicles.

SECTION 1: PRECISION FORGING

Closed-die precision forging is for making parts to net shape or near net shape. Conventional forging produces parts with excess material in the form of machining envelopes and allowances for "draft" or tapers on some of their surfaces. Tapers permit the part to be removed from the die. Although the part must then be machined to its final dimensions, which wastes material and can reduce strength, conventional forging often is the most economical choice. Still, precision forging offers distinct benefits in aerospace applications.

Precision forging yields uniformly strong parts with little or no excess material. The process thus avoids machining, which can reduce the strength of a part by cutting across the grain structure of the material and unbalancing internal stresses. The retained, as-formed strength of the part increases the certainty of its integrity in service. Precision forging dies cost more than conventional forging dies, but in many cases the difference can be offset by as few as a dozen parts. The reason, again, is that precision parts can be mated with other parts without machining. Given the costs of setup and machining, particularly in a three or five axis mill, the savings in net cost per part becomes very important.

Precision forging reduces costs by reducing the raw materials and machining required to attain net shape. The improvements this process offers in the properties of parts are not yet a major consideration in its selection over competing processes. Precision forging is used mainly with aluminum alloys, but also with titanium alloys, nickel base superalloys, and steel. This discussion focuses mainly on aluminum and titanium, but the issues and problems raised apply generally to other metals, including the new alloys now coming on the scene.

Because cost reduction is the primary motivation for using precision forging, the process often must compete with other processes. Depending on the metal involved, and the size and shape of the part, these processes may include machining from stock, conventional forging, investment casting, and powder metallurgy techniques. Further, complete precision in forging is not always the best approach - with complex parts, for example, cost sometimes might better be minimized by combining near net shape forging with machining or chemical milling.

The costs of machining and raw materials are not the only factors involved in comparisons of process economics. The installed cost of a precision forging reflects forging setup time (to prepare forging equipment for production runs), whatever machining is needed, machining setup times, finishing of parts, and the costs of engineering and tooling amortized over the number of parts to be made. Competing processes have their own characteristic processing costs and attendant installed costs. The many variables involved forbid flat statements on relative costs. As a benchmark, however, it can be said that precision forging of aluminum alloys may offer a cost reduction of up to 90% compared to parts machined from stock (hogouts) when large numbers of parts (more than 200) are involved.

LEVEL OF SAVINGS

The savings achieved by precision forging is a function of factors that include the material, *geometry*, *complexity* of contoured surfaces, and initial - final weight ratio. Cost savings typically average much greater than 50% for extra complex parts with contoured surfaces that *otherwise* would be machined from thick plate, bar, or billet. Significant savings also can be realized when a design that would normally be composed of many small detail parts is made instead from one precision forging. The estimated savings achieved by using precision forgings instead of hogouts for three parts on a future aircraft system is shown in Table 1-1; the parts are a frame support, an attach fitting, and a bulkhead fitting.

The cost avoidance estimates for using precision forgings, listed in Table 1-1 are based on building 100 aircraft, a very large quantity. The assumptions underlying Table 1-1 can be used to show that the number of forgings in a lot affects the relative cost of the two fabrication processes. If forgings for six or fewer aircraft are ordered (12 forgings of a kind), machining from mill products is the more cost-effective approach.

Reduction of machining conserves raw materials, but the cost savings are usually not economically significant with relatively inexpensive metals like aluminum alloys. The savings becomes more important with more expensive materials such as titanium, aluminum-lithium, metal matrix composites, and powder metallurgy materials based on rapid solidification technology.

Conservation of materials in its own right is not generally a primary consideration in decisions on whether to use precision forgings. But conservation is a growing national concern. In this vein, McDonnell Douglas estimates that use of precision forgings on a typical fighter aircraft (the F-15) can save some 3,000 pounds of aluminum alloy (and the associated energy *content*). The savings on 1,000 aircraft - 3 million pounds - would be enough material to build the aluminum components on 38 F-15s.

FORGING TECHNOLOGY

The technology of aluminum precision forging is effective but highly *empirical* - based more on practical experience than on scientific knowledge. Its benefits are being extended to more and more aircraft parts, as indicated by the steady increase in *the plan view* area (PVA) of parts that can be forged. Forging PVAs of up to 200 sq. in. is a proven technology, and larger PVAs are close to that status. Parts with PVAs up to 400 sq. in. have been produced on 10,000-ton presses, and PVAs up to 600 sq. in. on 35,000- and 50,000-ton presses. Although forging parts with these large PVAs is known to be feasible, the limitations are less clear. The metallurgical equivalency of precision aluminum forgings with conventional forgings, plate, and hogouts has yet to be determined.

Titanium precision forging has great potential for *reducing* costs. It needs further development, however, and, like aluminum precision forging, is highly empirical. The limitations of the process include the high cost of dies, which *must* work at the high forging temperatures (usually above 1700° F) required to deform titanium. The process also is size-limited. Although parts

MACHINED HOGOUT	$7180		TOTAL OF 3 PARTS*
PRECISION FORGING	895		TOTAL OF 3 PARTS*
COST AVOIDANCE	$6285	/3 = $2095 PER PART	
500 PARTS (2 PER SHIP)			1000 PIECES
2095 × 1000 = $2M SAVINGS/AC			
200 M SAVINGS/100 AC			
PRECISION FORGING DIE COST	$81,500	/3 = $27166	EACH DIE
500 PARTS $13.5M DIES			
ROI = $\frac{200 - 13.58}{13.58}$ = 13.73			
			$186.42M

* A frame support, an attach fitting, and a bulkhead fitting

TABLE 1-1 MEGABUCK COST AVOIDANCE
FUTURE AIRCRAFT SYSTEM

Source: Northrop Corporation

exceeding 500 sq. in. in PVA have been made, a maximum of 150 sq. in. is the current industry practice. Development has been limited by run size - the number of parts to be made for the particular aircraft (or other program) - which often is not enough to amortize the cost of the dies. For this reason, only about four shops supply titanium precision forgings, and users, therefore, are reluctant to design for the process.

THE FORGING INDUSTRY

The U.S. forging industry is one of the most critical elements of the nation's aerospace industrial base. Historically it has been a principal contributor to long lead times during periods of heavy aerospace demand. The industry is highly capital intensive and is characterized by relatively small companies and aging equipment, increasingly prone to breakdowns. The presses and auxiliary equipment would be especially vital during periods of surge or mobilization and might not be able to meet the demands placed on them during such periods. Further, only about 20 of the approximately 200 forging shops of various capabilities in this country make precision-forged parts for the multibillion dollar aerospace industry.

The industry's doubtful ability to cope with a surge in aerospace demand can be seen in terms of its limited capability in CAD/CAM and NC machining, the emerging technologies for producing dies and forgings. One commercial aircraft program, released for production with 1,200 precision forging configurations, would tie up the industry's entire capacity in these technologies.

Forging Bottlenecks

Studies of the precision forging industry have revealed several bottlenecks that impede productivity and could seriously impair a surge/mobilization effort. These bottlenecks include inordinate use of critical equipment for die tryout and proofing rather than production of hardware, outdated methods of die design and fabrication, mismatches between heat treating and hammer/press capacity, and lack of adequate techniques for materials handling and production control. All of these factors lengthen forging lead times during periods of high demand. Typical variations in lead time as related to aircraft deliveries are shown in Figure 1-1.

The extensive analysis of the Air Force's primary industrial base, <u>Blueprint for Tomorrow</u>, conducted by the Aeronautical Systems Division, found that forgings are a driver of costs and lead times that affects virtually all aerospace products. One of the recommendations that resulted from <u>Blueprint</u> was that a comprehensive productivity improvement and manufacturing technology implementation program be developed specifically for forgings.

THE CASE FOR PRECISION FORGING

A sound investment strategy in precision forging by the Air Force must rest not only on the costs of individual parts, but also on the cost of the finished aircraft. On this basis, the value of precision forging has yet to be documented. Department of Defense data show that the time required to build a military aircraft has remained at about 14 months for the past 30 years;

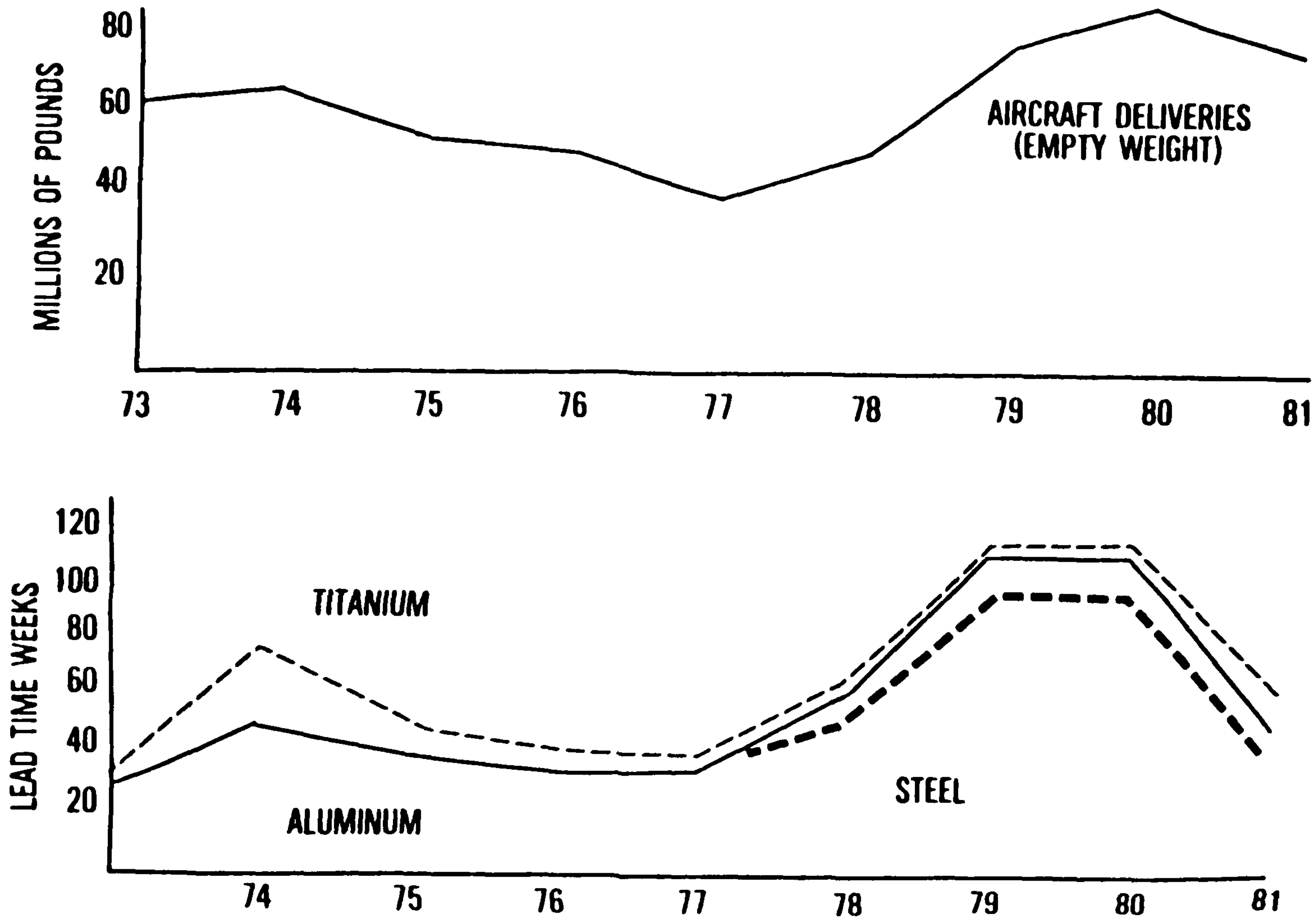

FIGURE 1-1 COMPARISON OF CHANGES IN LEAD TIME AND IN WEIGHTS OF AIRCRAFT DELIVERED, WITH TIME, FROM 1973-1981

man-hours expended per pound of aircraft structure, moreover, show no statistically significant change during that period. It can be argued, on the other hand, that manufacturing technologies must have improved if lead times and man-hours remained about the same for three decades while aircraft grew steadily more complex.

A principal problem in documenting savings on finished aircraft is the relatively small role of precision forgings. The major targets for savings in weapons systems are avionics reliability and support costs. On a more limited basis, the savings from using several thousand precision forgings on a large aircraft may not be as important as reducing the costs of holes, fasteners, and structural arrangement.

Authorities generally agree that precision forging conserves materials and can improve the throughput and physical properties of parts. The process potentially could improve surge capacity as well, but forge shops generally cannot afford to have capital tied up in idle capacity.

FORGING PROCEDURES AND MATERIALS

Preparation for a forging or forming process has four basic steps:

- Conversion of the finished part geometry to one or more forging geometries that can be produced by the precision process available.
- Analysis to determine the raw material input weight, geometry, and deformation conditions required to match the forging operation with the available equipment.
- Design of dies for the forging/forming steps needed to transform the initial stock into the final forged part. (Precision forging almost always requires three steps: blocking, preforming, and finish forging.)
- Selection of die material and manufacture of the dies, generally by conventional diesinking methods such as copy milling from a solid model or NC machining. Some die cavities are produced by electro-discharge machining.

Traditionally, these procedures have been handled using empirical guidelines, experience, and intuition. This approach is still common today, especially in smaller shops. It can lead to extensive effort in setup, die tryout, and modification, which may require more time than the ensuing production run. The emerging use of computer methods (covered later in this section) promises to upgrade the entire operation, although various barriers impede rapid adoption of such methods. Several additional problems and issues, technical and nontechnical, are involved in forging processes and materials.

Titanium Alloys

Titanium is precision forged in heated dies, which may be about 200° F cooler than the workpiece (hot-die process) or at the same temperature (isothermal process). Up to about 1700° F the metal can be forged in nickel base alloy dies. Higher die temperatures require the use of more expensive die materials such as TZM molybdenum, and operation under vacuum or an inert gas to protect the dies.

Given these circumstances, greater use of beta-titanium may offer a significant opportunity. Titanium occurs in two crystalline forms, alpha and beta, and titanium aerospace alloys may be all alpha, all beta, or mixed alpha-beta (with some subcategories). The alpha-beta alloys are the most widely used for aerospace forgings; beta alloys see relatively little use. Beta-titanium, however, can be forged in the range of 1300-1500° F as opposed to the 1750° F usually required for other titanium alloys. At the lower forging temperatures, less costly die materials can be used, forging lubricants perform better, and die heating poses fewer problems. An example of a beta-titanium forging material is the near-beta alloy Ti-10V-2Fe-3Al.

The grain size in a metal affects its properties, and some engineers are concerned about the large grain size of beta-titanium. The material has better fracture toughness than the more commonly used alpha-beta titanium, and has equivalent mechanical properties under static stress. Beta-titanium, however, may have lower strength under dynamic stress (i.e., lower fatigue endurance), and some designs may have to accommodate this difference.

The industry also sees a need for production of clean, low-cost titanium alloy powder that would provide highly reliable preforms for net shape forging. It is further desirable to incorporate in alloy development practices that relate compositions with processing conditions that provide materials with acceptable properties and characteristics. To date, alloys have not been developed this way.

Aluminum-Lithium

The forgeability of the advanced, light-weight, aluminum-lithium alloys is proving to be excellent, and demand for these new, high-strength materials is growing. Users report difficulty, however, in obtaining small orders on schedule and in various lot sizes of plate and billet. The apparent consensus is that multiple amounts of preformed billets of various sizes should be stockpiled at a common distribution center to offer timely and less costly procurement by small shops. This action would lead to reduced lead times and inventory costs throughout the industry.

Precision forging with aluminum-lithium alloys should be promoted. The marriage is a natural one, given the relatively high cost of the alloys and the metal conserving capabilities of precision forging.

Quality of Aluminum Forgings

Precision forging of aluminum can yield parts with better properties than are obtainable by some other forming processes because of its effects on grain flow lines and minimization of machining. MIL-Handbook-5, however, does not assign better properties to aluminum precision forgings. It has been contended that if the process does indeed impart superior properties to aluminum parts, the point should be substantiated and the data incorporated in MIL-Handbook-5. It has also been noted that to obtain the full benefit from precision forging, the forge plant engineer must design for optimum grain flow starting with the first, or blocker, die. One observer has said that the properties obtainable in precision forgings are no better than those of wrought stock, though his company prefers precision forgings anyway because of the cost savings.

Die Materials

Tooling - the design and manufacture of dies - is a major contributor to the cost of precision forging. In addition to the technological lag in tooling practices, improved or less costly die materials are a pervasive need, especially for use at high temperature and pressure.

Pratt & Whitney, for example, sees need for stronger, more creep-resistant dies that will stand the pressure needed to get closer to net shape in isothermal forging of jet engine parts of titanium and nickel base superalloys using the company's Gatorizing process. The TZM molybdenum now used is acceptable, but expensive; the cost of making precision dies from this material (tooling cost) can exceed $200,000.

Wyman-Gordon reports a need for nickel base dies that can be repaired by welding. Suppliers of die materials, however, are not especially interested in the problem because the market is relatively small.

Small aluminum forgers would like to see the yield strength of die steels increased 30,000 psi at 750° F without an increase in cost.

Die Engineering

Development of better die materials, although highly desirable, is costly and time-consuming. More immediate benefits would be obtained by better die engineering - that is, making some design calculations. With few exceptions, this approach is not practiced today at large forging companies.

Lubricants

Several lubricants have been developed for use in forging titanium, but lubrication systems for service at high temperature are reported to be inadequate for both part-die lubrication and die-die lubrication in segmented dies. Glass base lubricants used for titanium precision forgings can limit run sizes by building up in the dies and requiring interruptions in the run to remove the lubricant. Some otherwise good lubricants attack nickel base dies at surface temperatures of 1600-1700 ° F. Among the needs are improved standards and quality control for lubricants used by the precision forging industry.

Die Heating

Hot dies are critical to achievement of the desired final geometry, flow lines, and mechanical properties of the part being forged. Forging dies are heated to and maintained at operating temperature by induction, resistance, or gas-fired infrared heating. Induction heating is most common for titanium forgings and gas-fired infrared for aluminum forgings. The method of heating in the die stack and the assembly of the die stack itself must provide uniform temperature from the surface of the die to the base plate of the press to produce dimensionally accurate forgings and to reduce the potential for die failure. Factors that affect die heating include die-stack materials, which are selected to withstand forging pressure at high temperature and to accommodate large temperature gradients from die to base plate. Because die-stack design varies with the heating method used, and die heating directly affects press setup time, improvement of die-heating systems offers significant opportunities to reduce costs.

COMPUTER BASED METHODS IN PRECISION FORGING

Computer based methods promise significant gains in efficiency and product quality in precision forging. Current efforts are focused mainly on CAD/CAM, but work is also under way on the broader concept of CAE.

CAD/CAM has two basic uses in forging technology. One is the preparation of drawings of parts and dies and generation of NC tapes for controlling the manufacture of dies by the methods mentioned earlier. The second use of CAD/CAM is analysis of the forging process - predicting stresses, metal flow in dies, temperatures, loads, and energy parameters.

The use of CAE/CAD/CAM for drafting and NC machining is growing in the forging industry, but is not widespread, in part because of the costs of introducing the new technology and a shortage of qualified manpower. The use of these methods in analysis of forging operations is less well developed and is employed by relatively few forgers in this country and abroad.

The Air Force Program

CAD/CAM holds significant interest for the Air Force, which in 1978 launched a basic research program designed to support the development of an advanced computer aided engineering system for metalworking processes. This effort led to the Air Force Materials Science Program in Forging, based at AFSC's Wright Aeronautical Laboratories, Dayton, Ohio. The program has three parts: the Processing Science Program, the In-House Program in Powder Metallurgy Process Modeling, and the Manufacturing Science Program in Die Design and Manufacturing for the Forging Process.

A major effort in this work is the development of a computer program called ALPID (Analysis of Large Plastic Incremental Deformation) based on the finite element method. ALPID is a generic program because it can be used to analyze any of the common metal forming processes and can be applied to ceramics and polymers. The program is designed on a modular basis because the Air Force anticipates that it will serve ultimately as the heart of a CAE system for metalworking. In net shape processing such a system would connect all functions, from planning through engineering, processing, and factory scheduling and control; the system's capabilities would include feedforward and feedback of data among all functions.

ALPID has three analytical modules: ALPID, for the isothermal condition; ALPIDC, for compressible powder metallurgy materials; and ALPIDT, for conventional hot working conditions. As an example of the modular approach, forging dies can be designed by combining ALPID (isothermal) with a heat transfer module to simulate hot die (nonisothermal) forging.

The goal of the Manufacturing Science Program is to develop a CAE/CAD/CAM procedure for the design and manufacture of forging dies (precision, isothermal, hot die, and conventional). The procedure is based on computerized simulation and is designed to minimize the need for experienced tool designers and tool and die makers. The prime contractor for the program is Shultz Steel; the first tier subcontractor is Battelle Columbus Laboratories. The work is scheduled for completion during fiscal year 1988.

The program will disseminate the CAE/CAD/CAM technology to interested U.S. aerospace companies and help interested U.S. forging companies to implement the technology. Once implemented, the technology is expected to:

- Reduce lead times and the costs of designing and making dies.
- Reduce setup time.
- Improve productivity and surge capability.
- Improve response to small lot orders.
- Increase the consistency and quality of forgings.
- Reduce dependence on skilled tool and die makers.
- Make net and near net shape forging more cost-effective.

Barriers to Computer Methods

Several CAD/CAM systems are available commercially, and there is no doubt that computer methods can do a great deal for precision forging. McDonnell Douglas has developed its own computer based forging design system; the company estimates that a forging can be designed with this system in one-tenth the time normally required by manual methods. Nevertheless, CAD/CAM faces barriers in the precision forging industry.

One barrier is cost. CAD/CAM systems are expensive, and it is difficult to justify them in terms of conventional return on investment methods. One small forger that is using CAD/CAM for diesinking reports that it is not cost-effective, but expects matters to improve as its programmers gain experience. In any event, the company believes it has no alternative to CAD/CAM in view of the shortage of journeyman diesinkers.

The inability of forgers to acquire and use CAD/CAM can reduce the utility of the equipment to customers who have it. This is so because exchange of forging geometry in digital form, bypassing drawings, is an important benefit of computer methods. An airframe maker says it can reduce lead time by a month if the forger has compatible computer equipment and programs.

A second barrier to growth in CAD/CAM applications is the shortage of engineers qualified to apply the method to design and related operations. This problem would be eased by incorporating into CAD/CAM systems sophisticated computer programs (expert systems) that supplement the engineer's knowledge of both the computer system and forging design. Such programs will be desirable in the long run for routine use, but they remain to be developed.

Perhaps the major long term barrier to applying CAD/CAM in precision forging is the absence of a comprehensive data base for use in design and process simulation. The necessary data would include, for example, the thermal and physical properties of all materials used in forging and data on friction for various combinations of workpiece, die, and lubricant materials. Such data exist in the industry, but are dispersed and have not been collected systematically, thus they are not readily accessible to contractors.

NONTECHNICAL CONSIDERATIONS

Nontechnical problems also confront users and suppliers of precision forgings in the aerospace industry. They fall under the general headings of lead time and manpower.

Lead Time

The lead times required to obtain precision forged parts using new dies in the aerospace industry today are running 40-50 weeks for larger presses (up to 3500 tons) and 20-25 weeks for smaller presses (1500 tons and below). Repeat orders run 15-25 weeks. The forging industry has been expanding significantly, but lead times will likely lengthen if aerospace demand grows as expected in the immediate future.

A major problem, particularly for small forgers, is the cyclical nature of the aerospace industry. One small company, for example, has lead times of about 40 weeks. The company is expanding moderately, but if it were to expand enough to cut lead times to 20 weeks, it would risk insolvency due to the heavy expense incurred by idle capacity during the inevitable slow periods.

Small forgers that want to expand capacity may seek to buy used equipment and refurbish it, but report difficulty in identifying government owned surplus presses. A case in point is cited by Aluminum Precision Products, which has 10 presses, but has not bought a new one since its inception in 1965. The company once bought a press from a salvage dealer that it could have bought earlier at lower cost from the government had it known the press was available as surplus.

Coping with Lead Times

Long lead times make it difficult to get parts on early production aircraft. To exploit the benefits of precision forgings, there is no substitute for catching early aircraft. If hogouts are used and are providing satisfactory parts for production aircraft, subsequent efforts to switch to precision forgings sometimes meet resistance because they may require costly requalification if the change is made. The resulting delay reduces the savings available from precision forgings by reducing the amortization base for the cost of dies and the associated operations. Grumman, Vought, and General Dynamics report that some form of advance funding, such as multiyear procurement, can be quite helpful to user and supplier in coping with long lead times. Vought, for example, says it designs for precision forgings and puts their full cost in the budget for the production design on which it bids the contract. It is then possible to authorize the purchase of die-block materials and the related work relatively early in the program. With this procedure, Vought historically has been able to catch early production aircraft with precision forgings.

Manpower

Both users and suppliers are worried by the shortage of design engineers, diesinkers, and NC technicians. Many new engineers never have designed a forging by conventional methods or by CAD/CAM. Further, it is difficult to explain modern precision forging technology to uninitiated design engineers. The need is not to turn all designers into forging specialists, but to familiarize them with the state of the art so that a very few forging specialists can support many nonspecialist designers. As noted earlier, CAD/CAM with expert systems programs can help, but not immediately.

It should be pointed out that at least one forger, Ladish Company, says the shortage of engineers is not a major barrier. The company finds that properly trained technicians can be used for CAD/CAM.

The lack of trained people in die design and manufacturing would appear to require greater use of die design manuals and other aids. Diesinkers especially are in short supply. During 1978-83, almost 800 journeyman diesinkers nationwide, retired or otherwise left the field. The Los Angeles area currently has only 32 apprentice diesinkers.

NC machining can ease the diesinking problem, but technicians in this field are also in short supply. Only three die shops in the Los Angeles area can handle NC tapes. Besides the shortage of NC programmers, the performance of programmers doing the same job varies widely, which suggests that the industry should recognize minimum qualifications to promote more uniform performance.

Forging technology, especially die technology, is understood by relatively few experienced people. Efforts should be made to translate their know-how into expert systems software.

Several efforts are aimed at easing manpower shortages in die design and manufacture. The Forging Industry Association (FIA), for example, has a five-day training program for die designers that includes an introduction to computers. The program mainly involves steel forgings and does not focus on precision forgings because the field of application is too small. It is conceivable, however, that FIA would cooperate in a modest training effort.

In a second program, the die makers' association in Dayton, Ohio, is providing 25 scholarships annually in NC machining or programming. Also, representatives of the aerospace industry in the Los Angeles area have explored ways to encourage community colleges to promote training of NC programming technicians.

COMMENTS ON LARGE PRESS STUDY

The committee discussed at length the Large (200,000-ton) Press Study during the workshop on precision forging and later in committee. We concluded that the large press capability is not particularly relevant to net shape forgings, so the topic does not appear in our recommendations or road maps. Nevertheless, we offer the following comments.

The keynote speaker for the workshop, Sol Love, noted that a sound case for funding a 200,000-ton press has not yet been made. A compelling argument must involve not just the press, but also the integration and automation of the ancillary equipment. One question that must be answered is how to assure that the dies can be used, if necessary, on another press without rework; the existence of two 200,000-ton presses would ease the die-transfer problem.

It was pointed out that, typically, the larger the forging, the fewer are made, and the higher the cost per pound. Further, the larger the forging, the more difficult it becomes to justify economically the manufacture of near net shape forging designs. In conventional forging, orders for smaller lot sizes lead to practices based on fewer die operations and, therefore, less contour refinement and more blocker conventional forging designs. As PVA increases, higher stresses are developed in the dies, shortening useful life and dimensional conformance.

The largest presses in the United States are two 50,000-ton units, both installed in 1955, and the view was expressed that a jump to 200,000 tons might be ill-judged. One proposed alternative is to build four 50,000-ton presses incorporating the best technology available. Requirements exist for 50,000-ton presses, but such equipment would not meet the needs expressed by proponents of a 200,000-ton press.

Some Air Force, Navy, and commercial aircraft still use very large blocker forgings made on one of the 50,000-ton presses. The Air Force study 15 years ago was initiated because of the 15 blocker forgings of aluminum, weighing almost 350,000 pounds total, that comprised the five main frames of the original C5A. Approximately 90% of the metal was removed by machining to finish these forgings. This procedure is still used on the C5B now in production. Similarly, titanium blockers for the carrythrough structure of the 747 have more than 80% of the metal removed in finishing.

RECOMMENDATIONS

The problems and issues in precision forging identified by the committee are stated here in the form of needs. We recommend that they be met to insure the development and maintenance of a healthy, technologically advanced precision forging industry.

1. Rapid further development and field application of the Air Force's ALPID program for CAD/CAM in metalworking and completion on schedule of the Manufacturing Science Program in Die Design & Manufacturing.*

2. Incentives for encouraging modernization of firms producing precision forgings by:**

   - Adoption of CAD/CAM.
   - Improved use of equipment.
   - Addition of capital equipment, including inspection equipment.
   - Financial partnership of prime contractors and subcontractors to increase investment and profitability.

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* The Air Force is sponsoring a series f Manufacturing Technology Programs responsive to this need, but funding was uncertain as of June 1985.

** In response to this need, the Air Force Systems Command, on September 13, 1985, awarded Phase I Technology Modernization contracts to five organizations: Aluminum Forge Co., Arcturus Mfg. Co., Chen-Tech Industries, Ladish-Pacific, and Ontario Forge. Duration of the Phase I contract is nine months.

- Provision of R&D funds directly to small forgers to permit them to improve the use of existing equipment and improve the quality of their products.

3. An organized effort by the aerospace industry and the Air Force, in cooperation with the Forging Industry Association, to develop training programs for precision forging die design and manufacture, including NC programming and machining. Such programs would include simple methods and computer assisted techniques.

4. Encouragement and funding of basic and applied research in net shape forging, including: prediction of metal flow; distribution of stress, strain, and temperature in the workpiece; and load and energy requirements during automation.

5. Expanded activities on the finite element and other methods to develop codes adaptable to analysis of precision forging, die design, lubricant selection, etc., and to remove existing barriers to use of CAD/CAM.

6. Encouragement and funding of additional research on methods for improving the properties of existing die materials and developing new die materials.

7. Improved and less costly die materials for forging titanium at higher than 1750 °F.

8. Research and development on die heating systems employing combinations of induction, resistance, and gas-fired infrared heating.

9. Investigation aimed at wider use of beta titanium in view of its properties and its forgeability at relatively low temperature.

10. Nickel base dies of higher, more consistent quality that can be repaired by welding.

11. Systematic development of a comprehensive data base on the properties and behavior of materials relevant to precision forging for use in the design of parts and dies by CAD/CAM.

12. Die steels for forging aluminum that are about 30,000 psi higher in yield strength at 750 °F than current materials, but at similar cost.

13. Better standards and quality control for precision forging lubricants and improved lubricants for use at high temperature.

14. A project designed to couple ALPID with a finite element method for measuring stresses in forging dies.

15. Multiyear procurement of aerospace components to ease the effects of long lead times for precision forgings.

16. Production of clean, low cost titanium alloy powder that would provide highly reliable preforms for net shape forging.

17. Much closer integration of the development of forging alloys with the needs of subsequent processing steps.

18. Quick die changing devices to reduce setup times and costs.

19. A program of refinement of process controls designed to increase the PVA capability of precision forging.

20. A systematic effort to expand the application of precision forging to the aluminum-lithium alloys in view of the metal-conserving potential of the process and the substantial cost of the alloys.

21. A stockpile of preformed aluminum-lithium billets at a central point to permit small forge shops to obtain small orders in oddlot sizes on schedule.

22. Incentives for modernization and expansion by makers of precision forging dies, including the adoption of CAD methods and NC machining.

23. A well organized effort to identify surplus government owned forging equipment for acquisition by interested, eligible forging shops.

R & D ROAD MAPS

We translated the foregoing needs into a road map for R&D in precision forging (Road Map 1-1) and a set of institutional issues and the actions that they call for (Table 1-2). The road map shows the time likely to be required to solve the technical problems named. Although analogous times cannot be readily specified for the institutional issues, they must be resolved in parallel with work on technical problems to create a sound industrial base in precision forging.

Following the road map is a numbered list of workshop speakers and the titles of their papers (which comprise Volume II of this report). These papers are cited where appropriate both in Road Map 1-1 and Table 1-2.

Action Needed	Action Item Details	References [a]
Expanded Effort	Multi-Year Procurement	2, 18
	Improve Lead Times	2, 10, 13, 15 16, 17
Incentives	Added CAD/CAM	4
	Capitalization of Equipment	1, 7, 8
	Provision of R&D (Tech-Mod)	2, 4
Training	Tool & Die Makers	12, 13
	CAD/CAM Operations	13
	Introduction of ALPID	4
Modernization	CNC Equipment	2, 13, 18, 20
	Computer Controlled Inspection Equipment	11, 13
	Data Base	4

[a] The numbers identify speakers who discussed these action items at Workshop 1. The material they submitted for publication appears in Volume II of this report.

TABLE 1-2 CLOSED DIE PRECISION FORGINGS, INSTITUTIONAL ISSUES

Item Description		Action Item Details	Time Phase, Years			References (a)
Technical or Institutional	Activities		1-2	2-5	5-10	
Technical	Data Base	Properties & Behavior of Materials	▬	▬	▬	4, 7, 10, 11
	Basic/Applied Research	Prediction of Metal Flow	▬	▬	▬	4, 6, 7, 12, 15
		Process Analysis	▬	▬	▬	4, 6, 7
		Load and Energy Requirements	▬	▬	▬	7, 4
		Interface Conditions	▬	▬	▬	7, 4
		Die and Process Design	▬	▬	▬	4, 6, 7
		Process Modeling	▬	▬	▬	4, 6, 7
	Dies	Development of Die Systems	▬	▬	▬	5, 6, 8, 9, 12, 13, 21, 22
		Improvement of Existing Die Materials	▬	▬		5, 6, 21, 22
		Die Heating Systems	▬	▬		6, 21, 22
		Improved Die Lubricants	▬	▬		5, 6, 20, 21, 22
		Die Change Systems	▬	▬		20, 21, 22
		Design	▬	▬	▬	8, 18, 21, 22
	Product Materials	Improved Fabricability of T. Alloys	▬	▬		6, 9
		Improved Fabrication of Alum. P/M Alloys	▬	▬		19
		Improved Fabrication of Al-Li Alloys	▬	▬		13, 11
		Improved Fabrication of Al/Sic Alloys	▬	▬		12
	Product Geometry	Increased Plan View Area Capability	▬	▬		9, 11, 13, 14, 15, 19, 20, 22
	Software	Application of ALPID	▬			4,8
		Development of Finite Element Codes	▬			7
		Development of CAD/CAM/CAE Software	▬			4, 7, 8, 10, 12, 13, 17, 18, 19, 20

(a) Reference numbers identify speakers who discussed these action items at Workshop 1. The material they submitted for publication appears in Volume II.

ROAD MAP 1-1 CLOSED DIE PRECISION FORGINGS

WORKSHOP I SPEAKERS[a]

1. Love, Sol. Keynote Address.

2. Reed, M. J. U. S. Forging Industry: Technology Modernization Program Plan.

3. Workman, John F. Design/Cost Guide to Part Production Related to Forging.

4. Gegel, Harold L. Net-Shape Technology in Aerospace Structures: Air Force Materials Science Program.

5. Walker, Bryant H. Jet Engine Forging Procedures Applied to Net-Shape Forging.

6. Chen, Charlie C. An Overview on Titanium Forging Technology.

7. Shabaik, Aly H. Processing Fundamentals.

8. Altan, Taylan. Fundamentals of CAD/CAM Applications to Forging.

9. Melill, Joe. Usasge Needs at Northrop.

10. Richards, W. T. Closed Die Precision Forgings.

11. Henderson, Greg. Status of Precision Forging Use at General Dynamics.

12. Serfozo, Tibor. Status of Precision Forging Use in the Lockheed Corporation.

13. Hicker, James A. Boeing Corporation's Use and Future Needs for Near-Net and Net-Shape Forgings.

14. Lynch, Lloyd. Status of Precision Forgings in Helicopter Applications.

15. Zelus, Bruce. Application of Precision Forgings and Cost Effectiveness on the B-1B Bomber.

16. Wagner, Larry. Status of General Aluminum Forge, Inc.

17. Griffin, Tom E. Status of Aluminum Forge, Inc.

18. Spinelli, Mike. Aluminum Precision Products, Inc.: Its Capabilities, Products, and Motivations.

19. Nelson, Jim. Forging Operations at Vernon Plant - Aluminum Corporation of America.

20. Webster, B. J. Aluminum and Titanium Precision Forging at Martin-Marietta Aluminum Company.

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[a] The material submitted for publication by these speakers appears in Volume II of this report.

21. Daykin, Robert. Ladish Experience in Net and Near-Net Forging Production.

22. McKeogh, John. Titanium Precision Forging.

SECTION 2: EMERGING NET SHAPE TECHNOLOGIES

The techniques reviewed in this section are not new, but they are emerging technologies for the manufacture of high performance aerospace parts. They include: powder metallurgy, structural ceramics, hot isostatic pressing, consolidation by atmospheric pressure, superplastic forming, diffusion bonding, and coatings.

POWDER METALLURGY

Metal powders have long been used to make parts when the method offered economies in manufacture and, in some cases, when the parts could not be made in other ways. Only in the past few years, however, has it become possible to use rapidly solidified powders (RSP) for producing high performance parts using powder metallurgy (PM) techniques. RSPs are highly homogeneous and can be formed into shapes that are metallurgically much cleaner and also more workable than the products of ingot metallurgy. Pratt & Whitney designers assign 20% more strength to powder metal parts of the nickel base superalloy IN 100 than to castings of that material. In addition, some advanced aerospace materials can be made only by PM technology.

The primary uses of RSPs today are superalloy turbine and compressor disks for aircraft jet engines. No products made of RS aluminum or titanium alloys have yet attained full commercial status. Development of these materials is under way, but the near-term applications appear to be limited to the aerospace industry. An important goal of superalloy, titanium, and aluminum powder technology is buy/fly ratios of 2 or less for parts such as engine disks and rings, and airfoils, fasteners, and sheet-fabricated parts.

The methods for making RSPs vary somewhat with the base metal in the alloy. In general, however, the molten alloy is atomized by a high-velocity, sometimes updraft, stream of gas, typically argon or helium, or by throwing droplets from a disk rotating at high speed in an inert atmosphere. The RS product is sieved and blended to obtain batches of powders of the desired size distribution. The powder is then compacted and formed by suitable combinations of methods, such as isostatic pressing, extrusion, and forging. Powder metallurgy processing is capable of developing unique, tailor-made microstructures in the end product, and the densities of finished materials generally are 100% of the theoretical density of the particular alloy.

Superalloy Powder Metallurgy

The primary aerospace use for powder metallurgy, as noted earlier, is turbine and compressor disks for aircraft jet engines. At Pratt & Whitney, for example, these parts are made of the nickel base superalloy IN 100 (for the F100 engine). As much as 1800 pounds of superalloy powder is sealed in a container under vacuum, densified, and extruded into billets that serve as stock for subsequent metalworking operations. The uniformity and relatively fine grain size of this material significantly enhance its workability compared to ingot based stock. The homogeneity also enhances the sensitivity of nondestructive evaluation methods, such as ultrasonic inspection, in detecting otherwise hidden defects in parts made of the material. Pratt & Whitney makes disks from superalloy PM billet to near net shape using its proprietary forging process called Gatorizing.

The higher thrust-to-weight ratios planned for the next generation of jet engines will call in part on the capabilities of powder metallurgy. RS technology powders are being used, for example, to make superalloy turbine blades and vanes more durable than those in use today. These airfoils are expected to withstand higher turbine inlet temperatures without the protective coatings now used.

A prospective problem with new PM superalloys is the apparently insufficient attention being paid to workability. The goals of the alloy developers are strength and durability in the engine environment. Too little forethought is given to limiting process parameters - such as allowable metalworking temperatures - that affect the fabricator's ability to deform metals into net or near net shapes.

A Need for Cleaner Powder

A general problem with PM superalloys is contaminants, particularly their effect on the low-cycle fatigue life (LCF) of parts. General Electric has done extensive research on the problem in the nickel-base superalloy Rene 95. The major contaminants, ceramic inclusions and voids created by trapped argon, are acquired during production of the powder. The General Electric research shows that the average LCF life of Rene 95 can be improved significantly by thermomechanical processing, such as extruding and forging, because it reduces the size of defects and disperses them through the alloy. Typically, reductions of 80% in area are generally believed to be necessary to disperse these grain-boundary contaminants. Still, the low-cycle fatigue life of PM nickel-base superalloys is limited by certain types of ceramic inclusions. They come from powder preparation equipment, specifically the melting crucible, the pouring tundish (basin), and the atomizing nozzle. General Electric believes that further substantial improvement of LCF life requires cleaner molten metal and a ceramicless atomization process.

Superalloys for PM processing currently are vacuum-induction melted and remelted. General Electric expects that improved melt-refining processes now in development, such as electroslag remelt and electron beam cold hearth remelt, will significantly reduce the amount of ceramics in the molten alloy used to make powder. In addition, a ceramicless powder production facility is at the conceptual design stage (Figure 2-1). The design envisions an automated, continuous powder making process with real-time monitoring and control. Essential to real-time process control are the sensors that provide the necessary feedback data, such as particle size distribution and melt chemistry. Some required sensors have not been developed, but General Electric believes that they are practical goals. By analogy, from experience with wrought steels, it appears that the added cost of cleaner RSPs would be repaid by improvements in the properties of products.

Aluminum Powder Metallurgy

Developments in aluminum powder metallurgy include alloys that retain their strength at up to 600° F. Alcoa has an iron-cerium alloy of this kind, and

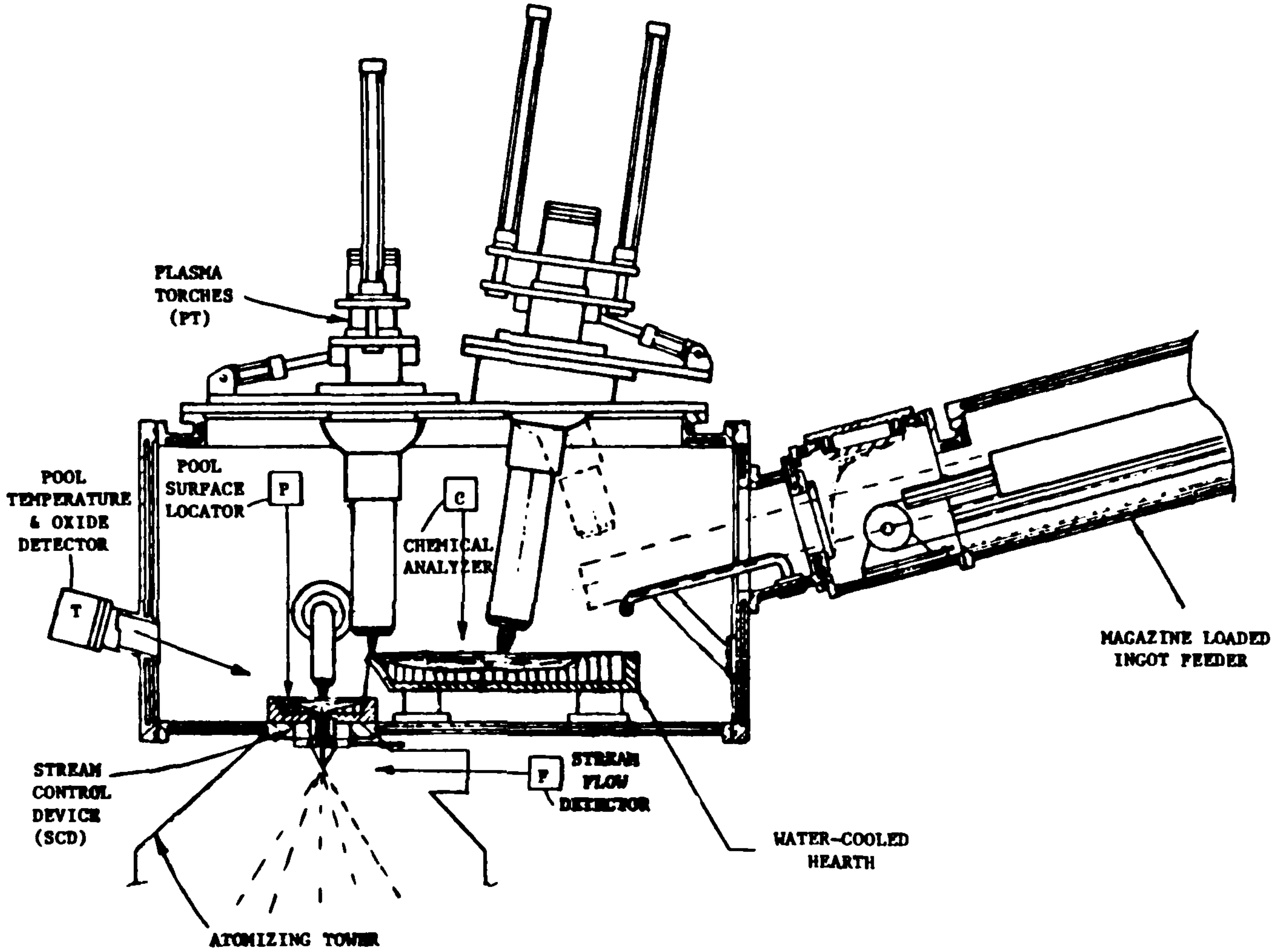


FIGURE 2-1 CONTINUOUS CLEAN PM PRODUCTION

Source: General Electric Company

Pratt & Whitney is working with an iron-molybdenum alloy. These materials are intended in part to replace titanium alloys in uses (e.g., jet engines) where the required heat resistance lies between the capabilities of conventional high-strength aluminum and titanium. In some such applications, the new materials will be competing with nonmetallic composites. Air Force programs designed to gain in-service experience with high-performance PM aluminum alloys are in progress. The substitution of these alloys for titanium would reduce both weight and manufacturing cost. The aluminum-iron-cerium and aluminum-iron-molybdenum RST-PM alloys also have outstanding corrosion resistance and are referred to as "stainless" aluminum.

For the future, Alcoa sees promise in several PM materials, including aluminum-silicon carbide composites. The powder metallurgy of aluminum-lithium alloys is of longer range interest, and Alcoa currently is doing little in that area, although very active in the conventionally processed material.

Among barriers to commercial use of PM aluminum alloys is the high capital investment for scaling up the operations.

Quality of Powder

A basic limiting factor for PM aluminum, as with the superalloys, is the quality of the powder and the consequent quality of the parts. Contaminants in powder (and billet) include organics, nonmetallics (oxides, carbides, etc.), metal slivers and rust, and furnace refractories. They originate at points throughout the powder-making process (Figure 2-2). These contamination problems can be corrected, but at a cost.

A major need, again as with the superalloys, is a consistent powder making process under real-time control. The most difficult tasks in meeting this need are development of a quantitative understanding of the powder making process and development of the necessary sensors to provide feedback data for process control. Some of these sensors, according to Alcoa, are new technology -- that is, they have not reached the operating stage in aluminum powder production. Such sensors include those for in-line (real-time) measurement of the composition of molten metal and powder and the particle size distribution in powder.

A four-year program is under way in Japan to develop ultrafine metal powders, which lead to controlled microstructure, fine grain, and superplasticity in the resulting metals. The U.S. has no such programs.

Titanium Powder Metallurgy

Both the Air Force and Navy are sponsoring programs designed to develop PM titanium alloys for net shape aircraft hardware (see also below, under Hot Isostatic Pressing). Among other developments, Pratt & Whitney is working on a nonburning titanium alloy such as the Ti-13Cu type. (Titanium parts, such as compressor blades in gas turbines, can be ignited by friction.) The creep strength of this PM material normally is poor, but can be much improved by dispersion of yttrium oxide particles through the metal. The dispersion-strengthened alloy is being tested and may be suitable for applications where only conventional superalloys are used now.

THREE PROCESS CATEGORIES

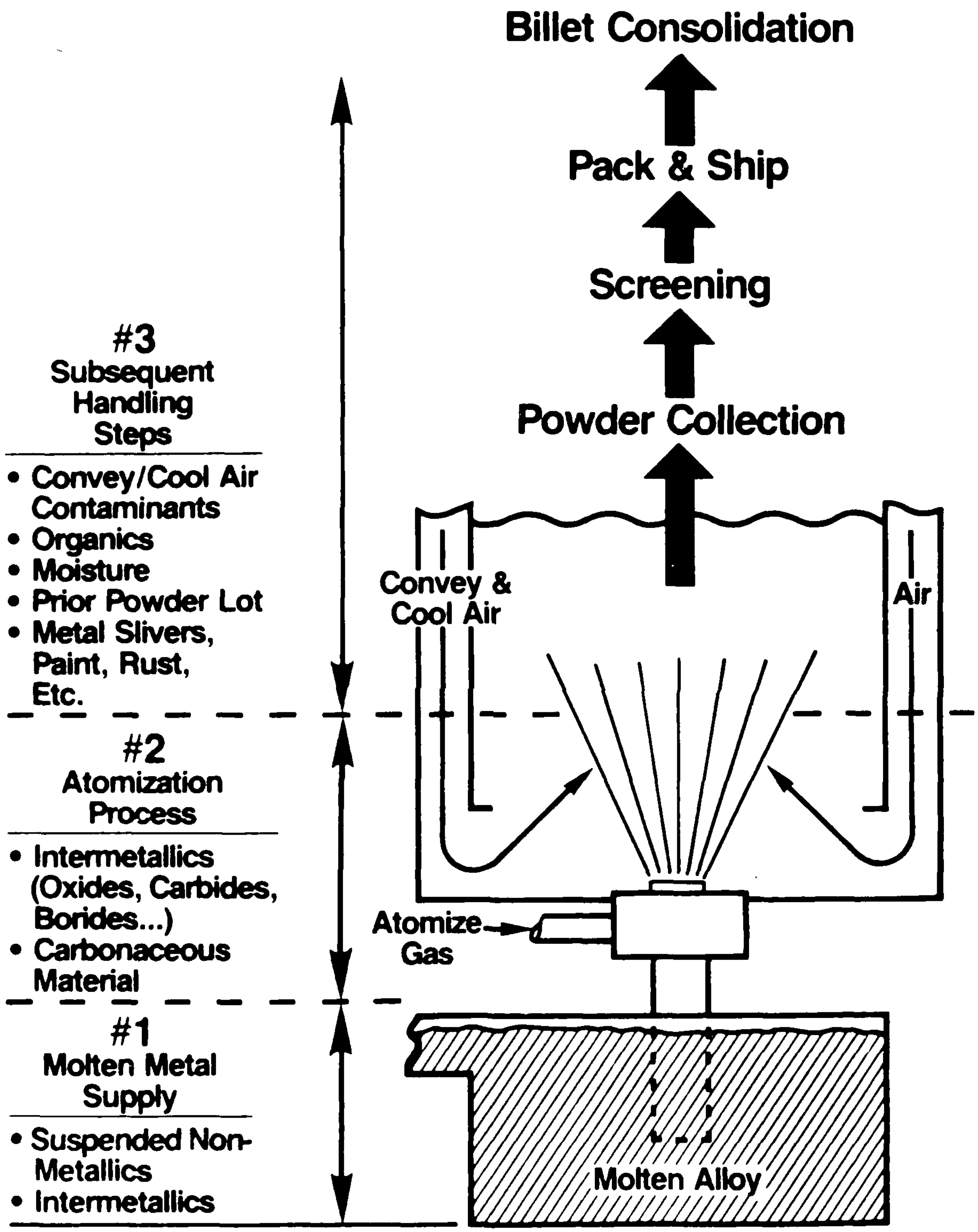


FIGURE 2-2 SOURCES OF CONTAMINANTS IN ALUMINUM PM PRODUCTION

Source: Alcoa Corporation

STRUCTURAL CERAMICS

The technology of structural (high-stress) ceramics lags well behind that of high-performance powder metallurgy parts based on rapid solidification technology. Ceramic products are widely used and many are mass produced. They include toilet bowls, spark plug insulators, substrates for microelectronic circuits, magnets, and optical waveguides (fiber optics). But ceramics remain an emerging technology for high-performance, biaxially stressed structural parts. One exception is the silica-based, heat-protective tiles on the space shuttle.

The main attraction of ceramics for aerospace use is their durability in hot environments (both thermal cycling and steady state hot environments), which far exceeds that of the best metals. In addition, newer ceramics like silicon carbide and nitride are much stronger than traditional ceramics. These characteristics have spurred considerable research and development during the past 15 years or so on ceramic parts for use in extreme environments, such as gas turbines.

Potential uses for ceramics in gas turbines include stators, rotors, transition liners, shrouds (abradable and nonabradable), and bearings and sleeves, according to Ceramatec, Inc. The most common causes of failure in such applications relate to contact stresses involving interfaces of ceramic components with other materials. In these designs, a compliant interlayer of a third material will often improve compatibility and prevent failure of the ceramic from high, localized stress. The base strength of the ceramics seems adequate. For most such applications, however, the data base for design is inadequate and, therefore, the reliability/predictability is low.

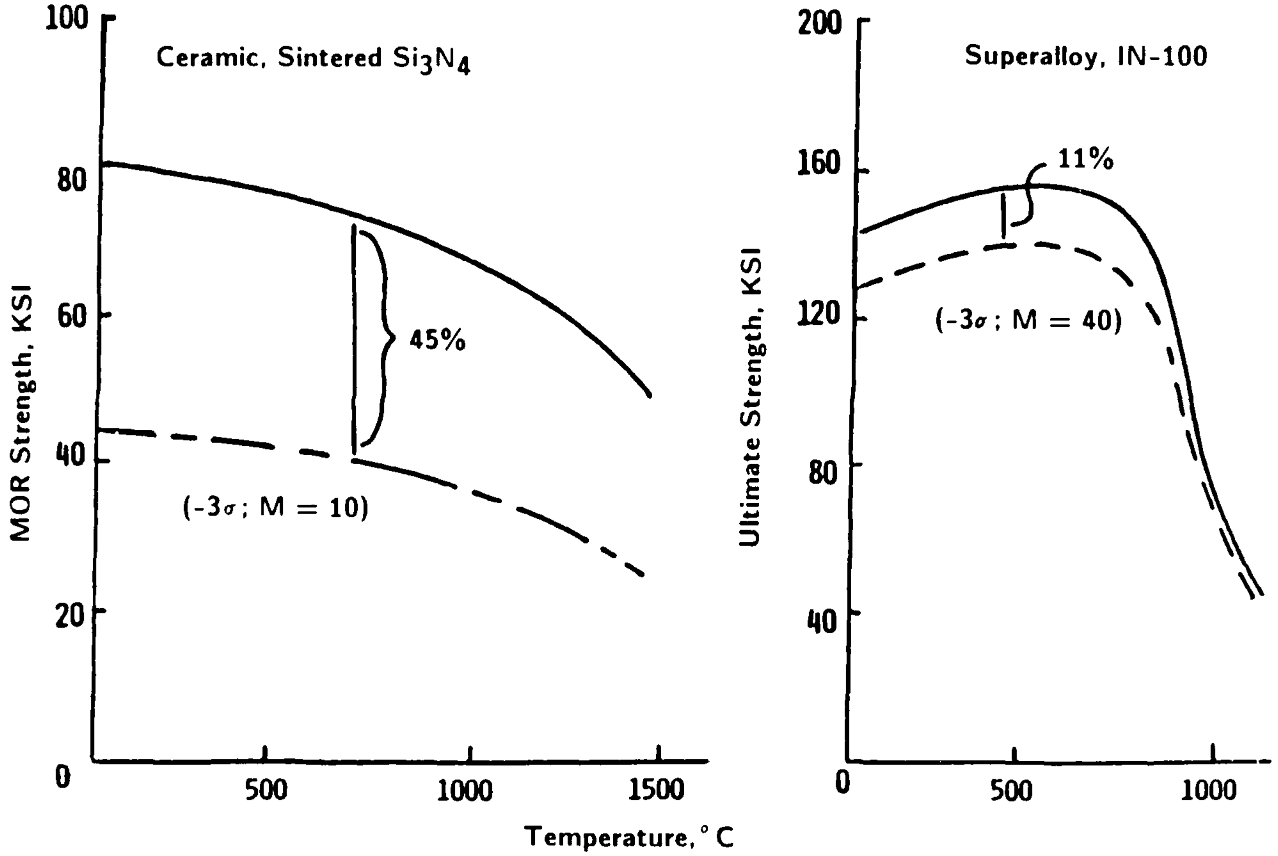
Fabrication of ceramic parts usually involves, first, forming a powder into the desired shape in one of several different ways. Once formed, the part is dried and sintered. It is essential that high-performance ceramic parts be fabricated as closely as possible to net shape -- the sintered material can be machined only with diamond or boron carbide tools, and the process is slow, labor intensive, and costly. Also, machining can reduce the strength of a ceramic part by damaging its surface. For ceramic turbine parts, Ceramatec reports, net shape means tolerances that often are closer than 0.001 inch and in most cases closer than 0.005 inch.

Reproducibility, Reliability

Important issues for structural ceramics are reproducibility and reliability. Ceramatec points out that measured properties of a silicon nitride can vary up to four times as much as the properties of a superalloy (Figure 2-3). Such variability reduces the usable strength of ceramics and complicates the work of the designer. Corrective measures include better control of the size distribution and chemistry of the starting powder.

Many engineers find ceramics unreliable as high-performance materials, partly because ceramics do not act like metals. The major difference between the two is the relatively low toughness (impact resistance) of ceramics. Toughness can be improved by means such as modifying microstructure and dispersing reinforcing particles or fibers through the material, but the design still must

VARIABILITY REDUCES THE USABLE STRENGTH OF CERAMICS



σ = Standard Deviation
M = Weibull Modulus
MOR = Modulus of Rupture - the nominal stress at rupture in a bend test

FIGURE 2-3 VARIABILITY REDUCES THE USABLE STRENGTH OF CERAMICS

Source: Lewis Research Center, NASA

accommodate the characteristics of the particular ceramic. Designs for high-performance ceramics in general are not optimum; one problem is that the design and the ceramic material must be optimized for the application at the same time through an iterative process.

Ceramic Processing

Processing is predictably an important link in production of high-performance ceramic parts. Although some such parts survive many hundreds of hours of testing, most are never tested at all because of macroscopic processing defects, according to Ford Motor Company, whose ceramic work has focused on automotive gas turbines.

Ceramic-forming processes include several types of pressure compaction of powder, slip casting (slip is a water-powder slurry), and injection molding. Steps common to each process are drying (removal of water or an organic binder) and sintering. Ceramic parts in the presintered, or green, condition are readily machined with ordinary cutting tools. All spark plug insulators, for example, are shaped by green machining before they are sintered.

Most ceramic components can be made by several processing routes. One process will generally be optimum for each part -- with lot size often the determining factor -- and no process will generally be optimum for all parts. All ceramic-forming processes, Ford says, require further development to improve quality, reproducibility, reliability, productivity, and cost. Good CAE is being done in plastics injection molding, for example, and this work could be applied profitably to ceramics injection molding. Better understanding is needed of the rheology of highly loaded suspensions of ultrafine particles and of the elements of predicting and controlling green density. Drying may take days or weeks, and tie up floor space; modeling this step by computer, which requires better understanding of the drying process, could save much development time. Also needed is improved and continuous sintering equipment, which must operate at about 3500 ° F for materials like silicon carbide and nitride.

For parts formed by processes like isostatic pressing, dry pressing, and slip casting, the cost of machining (including green machining) accounts for some 60% of the cost of the part, excluding tooling costs, according to analyses by GTE. These costs could be reduced substantially, and quality improved, by better controls in design and preparation of raw materials and in processing. Injection molding is the closest to a net shape process. It can handle complex shapes, says GTE, and machining cost accounts for only about 20% of the total. Tooling costs for injection molding, however, may run \$50,000 to \$100,000, 10 to 20 times the tooling costs for other processes.

GTE believes that manufacture of net shape parts by joining ceramic and ceramic and metal subcomponents offers opportunities to reduce costs because the subcomponents are easier to make than the complete part. Improved means of bonding ceramics to ceramics and to metals are becoming available; diffusion bonding may be applicable to ceramics.

Evaluation of Parts

Nondestructive evaluation methods for structural ceramic parts are relatively primitive, but are adequate so long as macroscopic defects are sufficiently common to control quality, which is generally the case today. Examination of parts visually and at very low magnification and conventional x-ray examination suffice in these conditions. When structural ceramics enter commercial use, all parts conceivably may require some type of real-time inspection for critical defects. The more economical approach would be to improve reliability to where the quality of structural ceramics could be assured by testing only parts selected by statistical sampling.

Consumer Products

An apparent misstep in the U.S approach to structural ceramics has been the tendency to concentrate from the outset on high-performance applications. This approach does not build an economic base nor create opportunities to develop production know-how. In contrast, commercial production of graphite-epoxy golf club shafts helped the evolution of high-performance graphite-epoxy materials in part by supplying a reason to produce graphite fibers in volume. Similarly, Japanese companies are commercializing high-performance ceramics in the form of cutlery and other consumer products.

HOT ISOSTATIC PRESSING

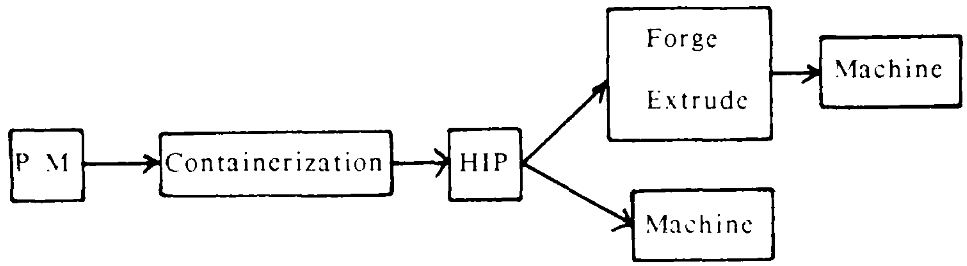
Hot isostatic pressing - simultaneous application of heat and high gas pressure - was developed in the 1950s to bond the components of a pin-type nuclear fuel element. Today HIP is used commercially for:

- consolidation of ceramic powders
- solid-state bonding
- defect healing and/or densification of precision investment castings, particularly titanium alloy and superalloy castings.

Most hot isostatic pressing in the United States is done at 15,000 psi at up to 2200° F. Advances in technology, however, have resulted in HIP units commercially capable of pressures to 45,000 psi and temperatures to 4000° F (this temperature and pressure are not available in the same unit). It has been reported that a HIP unit has been developed that will use pressures to 150,000 psi.

A commercial HIP unit, 60" diameter and 120" deep and operable to 15,000 psi and 2200° F, is under construction by Industrial Materials Technology, Inc., Andover, Massachusetts; on-line operation is scheduled for 1986. This unit is designed to permit HIP consolidation of investment cast Ti-6Al-4V compressor housings for production turbojet engines. Larger, high capability HIP units appear to be within the limits of current technology, should a need for them be recognized.

The HIP process has been used as a principal method of producing critical parts for turbojet engines. The parts are used either as-HIPed or after post-HIP consolidation procedures, such as forging or extruding. Conceptually, the two approaches are as follows:



The forging or extrusion may be by conventional means or by isothermal forming processes such as Gatorizing.

The use of as-HIPed or HIP + post-HIP thermomechanical processing is subject to differences of opinion. The use of as-HIPed parts was reported to have decreased during 1980-82, following the loss of an F/A-18 aircraft in September 1980. The crash was attributed to failure of a superalloy low-pressure turbine disk fabricated from as-HIPed metal powder. While the failure was never related conclusively to the part's being as-HIPed, use of this procedure decreased dramatically in a short time. It has been reported, however, that the decrease may have been coincident with other factors, such as recognition of the desirability of using finer powders and an attendant increase in the price of the powder, the drastic impact of the decreased availability of cobalt as a result of political turmoil in Zaire and Zambia, and the rise in the cost of money in the United States. These problems led to a return to use of more conventional materials and processes in new production engines.

It has also been reported, however, that post-HIP consolidation is required to decrease void sizes in the powder metal product. Decrease in void size (ceramicless powder) is reported to yield improvements in properties such as low-cycle fatigue, toughness, and short-time, elevated temperature mechanical properties.

We see no need to point out the numbers of parts that have been produced either as-HIPed or HIPed + post-HIP thermomechanical processing. Both procedures have found niches in product lines. Individual companies must evaluate the relative merits of the two processes in terms of their particular operations.

The [illegible] features of the HIP process suggest that its potential [illegible]. For example, use of HIP for near net shape [illegible] attractive. A second example is consolid[illegible] such as the aluminum alloy silicon carbide par[illegible] on a production basis. The HIP process is [illegible] product.

The HIP process warrants research funding aimed at developing a better understanding of the kinetics of isostatic densification over a wide range of pressures and temperatures. Whole new generations of materials for jet and rocket engines will require this advanced technology.

CONSOLIDATION BY ATMOSPHERIC PRESSURE

Consolidation by atmospheric pressure (CAP) has been developed by Cyclops Corp. CAP can produce near net shapes, and its distinguishing characteristics are simplicity and flexibility.

Powder to be processed by CAP is loaded into glass molds, which are then degassed and sealed. The molds are placed in sand in a large, reusable ceramic container, which is placed in an air-atmosphere furnace heated by electrical resistance. As temperature is raised to the sintering range, the molds soften and densification begins. The glass is totally molten at maximum temperature, but transfers atmospheric pressure to the preform and provides a protective coating over it throughout the process. The shape of the preform is maintained by the surrounding sand. Sintering completed, the molds are removed from the furnace, and the glass spalls from the preforms. The density of the consolidated parts depends on the sintering parameters, but ranges up to 99% of theoretical. The preforms may be worked to full density by forging, rolling, or extrusion; parts of complex shape may be HIPed to full density without containerization.

CAP has been applied to several alloys, but is used commercially only with high-speed tool steels. The technology is being evaluated under Air Force and Army contracts for making disks for various gas turbines. The main attraction of the process is its relatively low cost. The problems include lack of design data, insufficient development funding, and related difficulties in implementing a one-of-a-kind technology.

SUPERPLASTIC FORMING/DIFFUSION BONDING

Superplastic forming is based on superplasticity, the ability of a metal to elongate uniformly by several hundred percent or more without failing. A number of engineering materials exhibit superplastic behavior when deformed under the right conditions. Usually, the initial microstructure must be fine-grained, the rate of straining slow, and the temperature controlled carefully during deformation. In addition to enhancing uniform straining, these conditions result in unusually low forces. Superplasticity permits metals to be formed into complex parts using methods never before possible. In airframe and engine components in the U.S., superplastic forming is used principally with titanium sheet, but development is under way with high-strength aluminum sheet.

The requirements for superplastic behavior of titanium include a characteristic forming temperature and a fine-grain microstructure. Optimum conditions for the workhorse titanium alloy Ti-6Al-4V are 1600-1700° F and grain size in the range of 4 to 8 micrometers. The most common method of superplastically forming titanium is by forcing sheet into a die under pressure applied by an inert gas such as argon.

The value of superplastic forming is illustrated by a nacelle beam frame made by Rockwell International for the B-1 aircraft (Figure 2-4). Conventionally fabricated, the component had eight detail parts and 96 fasteners; the superplastically formed part was one part with no fasteners. Cost was reduced 50% and weight 30%.

Diffusion Bonding

Diffusion bonding involves intimate contact between parts at high temperature and pressure and diffusion of atoms across the interface. Titanium alloys, particularly Ti-6Al-4V, are well suited to the process. The metal in the interface area of the bonded parts has the microstructure and mechanical properties of the parent metal.

Superplastic forming and diffusion bonding (SPF/DB) are natural companions for fabricating titanium alloys: they have identical requirements for temperature, fine-grain microstructure, and an inert environment. SPF/DB processes can be conducted sequentially in the same equipment. The process can be used to fabricate a variety of complex shapes.

COATINGS FOR NET SHAPE PARTS

Aerospace applications of net shape parts may impose demands on materials that can be met only by resorting to protective or functional coatings. Such coatings may protect parts from heat, corrosion, or erosion, for example, or provide specific optical or electrical properties.

An important example of the value of coatings is the protection of airfoils in aircraft gas turbines by MCrAlY alloys (M may be nickel, cobalt, or iron). Precisely applied coatings of these materials, about 125 micrometers thick, increase the oxidation/corrosion life of the airfoils two- to threefold. Other examples of sophisticated coatings include thin layers of semiconducting amorphous silicon for photovoltaic uses, thin molybdenum films to provide infrared reflectance, and carbide and nitride coatings on high-speed cutting tools to improve wear resistance.

Deposition Processes

Coatings for these kinds of uses may be applied in a variety of ways: physical vapor deposition, including plasma, electron beam, and sputtering techniques; ion and chemical vapor deposition, in which films are deposited as they are produced by a chemical reaction; electrodeposition; and several others. The process used depends on factors such as the coating to be deposited, the rate and conditions of deposition, the shape of the substrate, and the desired adhesion of coating to substrate.

Deposition processes tend to be empirical - based on experience rather than detailed scientific knowledge - which handicaps scale-up of processes and their adaptation for new materials. The effects of plasmas on deposition and the characteristics of the resulting coatings, for example, are poorly understood. Similarly, current theories of adhesion do not adequately explain the observed

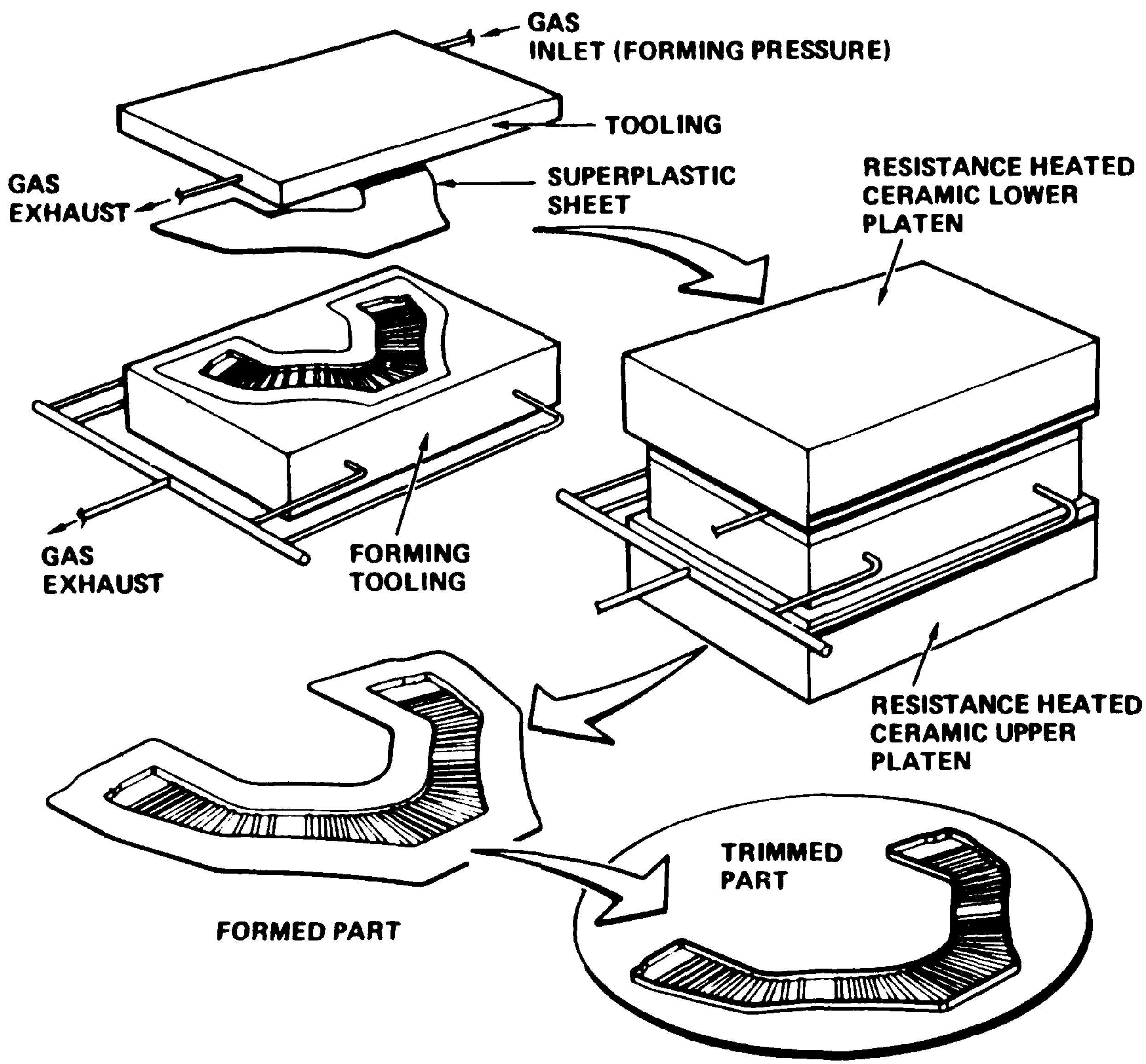


FIGURE 2-4 SUPERPLASTIC FORMING OF NACELLE BEAM FRAME FOR B-1

Source: Rockwell International Corporation behavior of some coating-substrate combinations. Also, incomplete understanding of the origins of residual stresses in coatings hampers the ability to predict and control such stresses.

Technology Transfer

Coatings technology would benefit from more effective technology transfer within the industry. Highly sophisticated, precisely controlled deposition techniques, such as magnetron sputtering, are used to deposit optical and electronics coatings, for example, and this know-how might be applicable to other kinds of coatings. Measurement of plasmas by methods such as optical emission spectroscopy and laser-induced fluorescence are commonly used in the laboratory to control the properties of coatings being deposited. The use of such methods has lagged behind the development of production scale, plasma-assisted coating processes.

Coatings for Gas Turbines

Military gas turbine engines currently incorporate several kinds of coatings to enhance the resistance of various parts to wear, heat, and oxidation-corrosion (Figure 2-5). The performance goals of the next generation of engines, however, will require significant improvements in coatings and other materials. The coatings requirements of these engines include erosion protection for titanium alloys, thermal protection for nickel base superalloys, and thermal-oxidation protection for carbon-carbon composites.

Erosion protection for titanium parts in engines will be needed especially for ground-support aircraft. A variety of coatings provide adequate protection. The difficulty is to devise systems that do not unacceptably reduce the high-cycle fatigue life of the titanium, and progress is being made in this area.

A major technological challenge is the development of a thermal barrier coating for superalloy airfoils in aircraft gas turbines. The goal is to add perhaps 200 ° F to the maximum operating temperature of the airfoils, with consequent improvement in the efficiency of the engine. Coatings in development are ceramic and are deposited in a vacuum by electron beam vaporization or low-pressure plasma spray. A significant problem with these coatings is inadequate resistance to spalling. Fundamental work is needed on the mechanisms of spalling, behavior at coating-substrate interfaces, the mechanisms of deposition of coatings, and the mechanisms of adhesion of overcoatings.

The most difficult engine-coating problem is protection of carbon-carbon composites. These materials offer the highest specific strength available today at very high temperature, but they require protection against oxidation at temperatures above about 800 ° F. Several coatings are being tried. A maximum operating temperature of 2500° F seems achievable in the near term; the limit for carbon-carbon would be about 3500° F.

GAS TURBINE ENGINE COATING USAGE

Current state-of-the-art

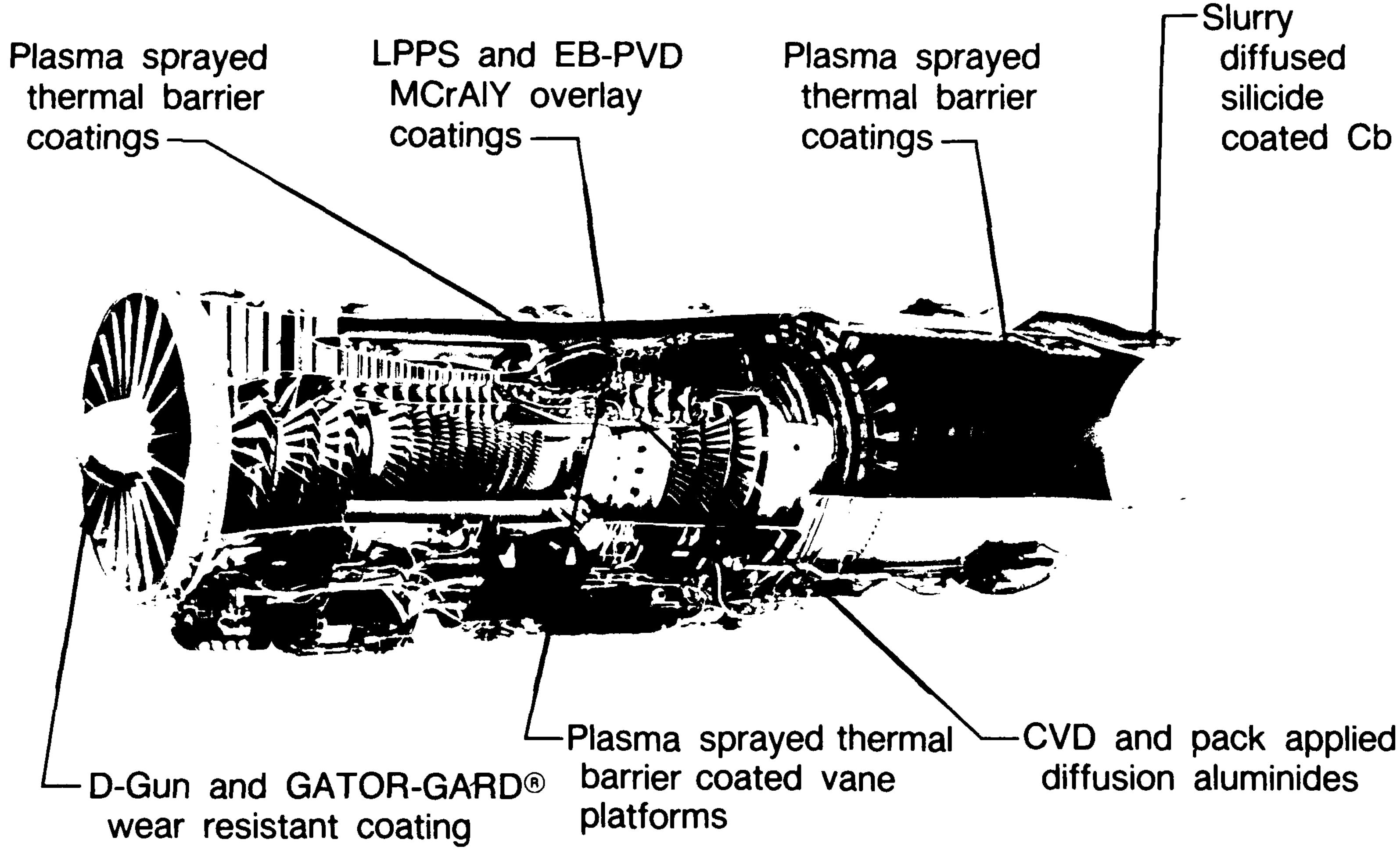


FIGURE 2-5 GAS TURBINE ENGINE COATING USAGE

Source: Pratt & Whitney

Generic Aspects of Coatings

Protective and functional coatings should be considered from the outset, as an integral aspect of design, rather than as means of solving immediate, unanticipated problems. Failure to do so can lead to significant delays in production because two years or more may be required to scale up a highperformance coating and coating process to the production level. Scale-up time could and should be reduced by strengthening the scientific basis of coatings technology. The impact of excessive scale-up times could be eased, however, by dealing with coatings as components of composite structures, i.e. - substrate-interface-coating - thus offering a designed protective system matched to the function of the part.

RECOMMENDATIONS

We have summarized current problems in emerging net shape technologies in the form of specific needs, which we have converted into five road maps, four in R&D and one for institutional relationships. Following the road maps is a numbered list of workshop speakers and the titles of their papers (which comprise Volume III of this report). These papers, and the applicable road maps (RM) are cited where appropriate with each of the needs. To facilitate application of emerging technologies for economical, net shape manufacture of high performance aerospace parts, we recommend meeting each of the following needs:

<u>Powder Metallurgy</u>

1. Closed-loop control of processes for producing rapidly solidified metal powders. This will require the development of quantitative process models, sensors for critical variables, and process controls. It will require that relationships be established between process variables and the quality and size distribution of powders. It may require modification of atomization processes to permit continuous operation. (2,3; RM 2-4)

2. Accelerated research and development on improved melting methods and ceramicless atomization for superalloy powders to support detailed design of a production system incorporating these features. (2,3; RM 2-2)

3. Integration of aluminum powder metallurgy technology into the design of new aircraft structures to insure that the technology is employed optimally and cost-effectively. (1,4; RM 2-5)

<u>Consolidation and Forming of Alloy Powder</u>

4. Development of process modeling and control of powder consolidation and improvement of microstructural control of powder metal parts. (2; RM 2-1 or 2-2)

5. Development of the scientific basis of hot isostatic pressing, process modeling and control of HIP, and understanding of effects of HIP variables on powder movement and bonding and final properties of HIPed parts. (1,2; RM 2-4)

6. More effective integration of alloy design with powder metallurgy manufacturing of net-shape parts. (12; RM 2-1, 2-2)

Structural Ceramics

7. Scale-up of laboratory fabrication processes for structural ceramics to the commercial level (8). Better understanding of structural ceramic forming processes, the sensors and controls needed to place these processes under closed-loop control, and the associated data bases. (5,6; RM 2-5)

8. More effective integration of design, manufacturing, and end use of ceramic parts to ease the difficulties of optimizing design and ceramic simultaneously for the particular application. (5; RM 2-5)

9. Accelerated development of the ceramics-oriented aspects of NC and computer NC machining, joining, NDE, and HIP. (7)

10. An expanded range and volume of structural ceramic products, including consumer products, to support the development of manufacturing experience and sources of supply. (RM 2-5)

11. A wider range of domestically produced ceramic raw materials, including high-quality powders and reinforcing particles and fibers. (6; RM 2-3)

12. A truly multidisciplinary approach to ceramics, involving ceramists, but also chemists and other specialists, including chemical, mechanical, and systems engineers. (5; RM 2-5)

Vapor Deposited Coatings

13. Further development of the scientific basis of deposition processes and development of process models, sensors, and controls required for real-time control of such processes. (9,11; RM 2-4).

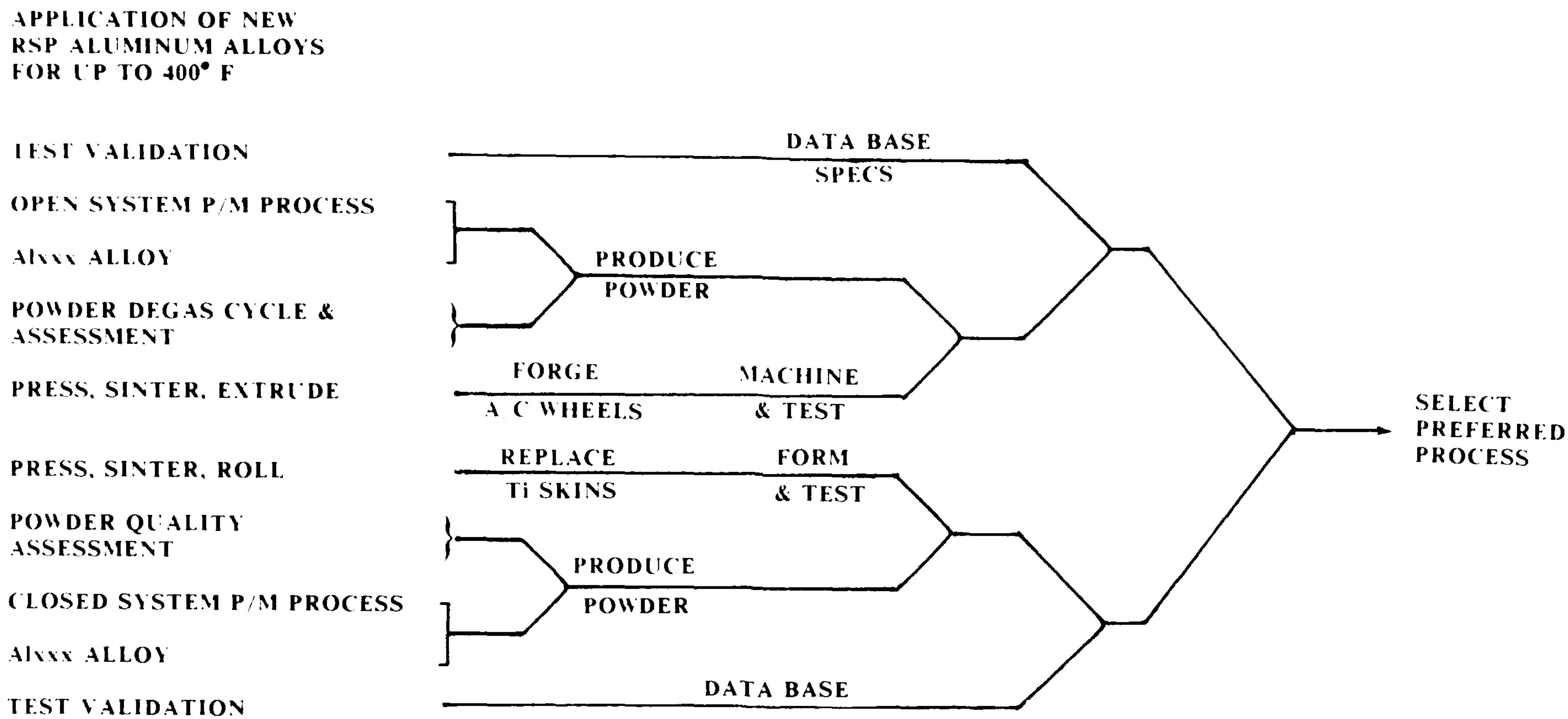
14. Deeper understanding of the mechanisms of adhesion and the causes of residual stress in coatings. (9; RM 2-4)

15. Improved definition of areas where coatings can benefit near net shape processes. (14; RM 2-5)

16. Better technology transfer in the coatings industry, such as the transfer of optical emission spectroscopy and laser induced fluorescence from current laboratory status into production. (9)

R&D ROAD MAPS

The road maps that follow concern technological and institutional needs that we believe deserve special emphasis now. The needs specified above extend well beyond those covered by the road maps. We believe, however, that for many of them, further information on industrial plans and circumstances is required to assure that government spending would be acceptably cost effective or that the resulting technology would be satisfactorily transferred to advance the state of the art and provide specifications and standards.



This program, designed to exploit the application of new "stainless" aluminum alloys for high strength/high temperature application, is comparing the closed-loop system and open systems for powder production, both coupled to an optimum consistent vacuum degas of the powder.

ROAD MAP 2-1 METAL POWDERS: ALUMINUM ALLOYS

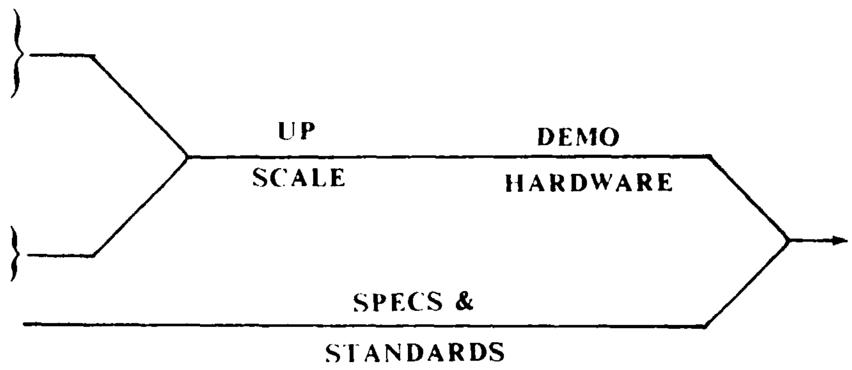
HIGH PURITY SUPERALLOY POWDER

- CLOSED-LOOP ATOMIZATION
- INTEGRATION WITH RSP
- IMPROVED MELTING

CONSOLIDATION & FORMING

- COLD PRESS, SINTER & EXTRUDE
- HIP EXTRUDE, FORGE

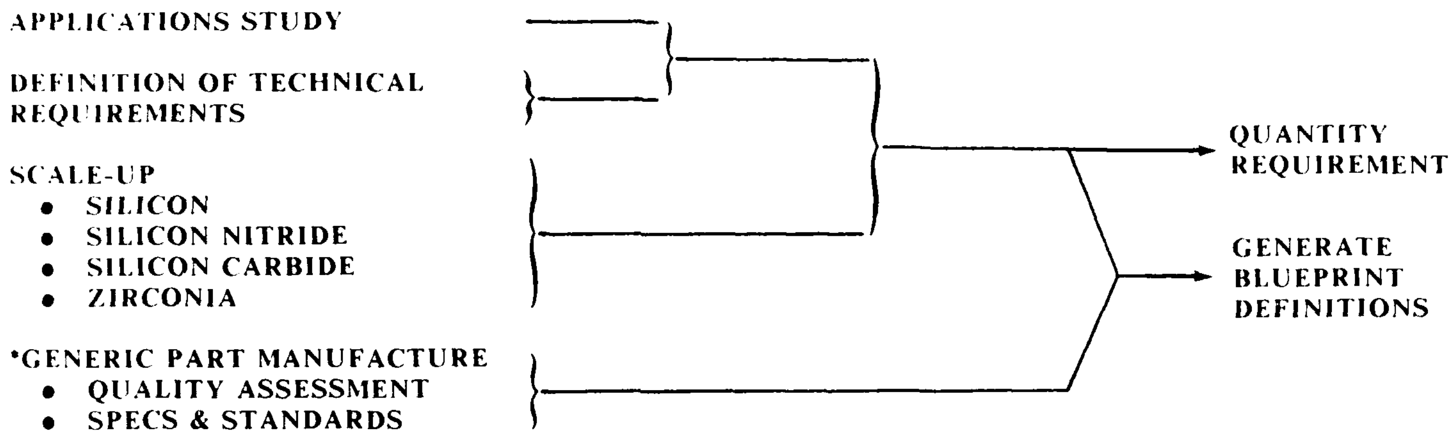
TESTING, VALIDATION



Closed-loop control of processes for producing metal powders will require the development of quantitative process models, sensors for critical variables, and process controls. It will require that relationships be established between process variables and the quality and size distribution of powders. It may require modification of atomization processes to permit continuous operation.

ROAD MAP 2-2 METAL POWDERS: SUPERALLOYS

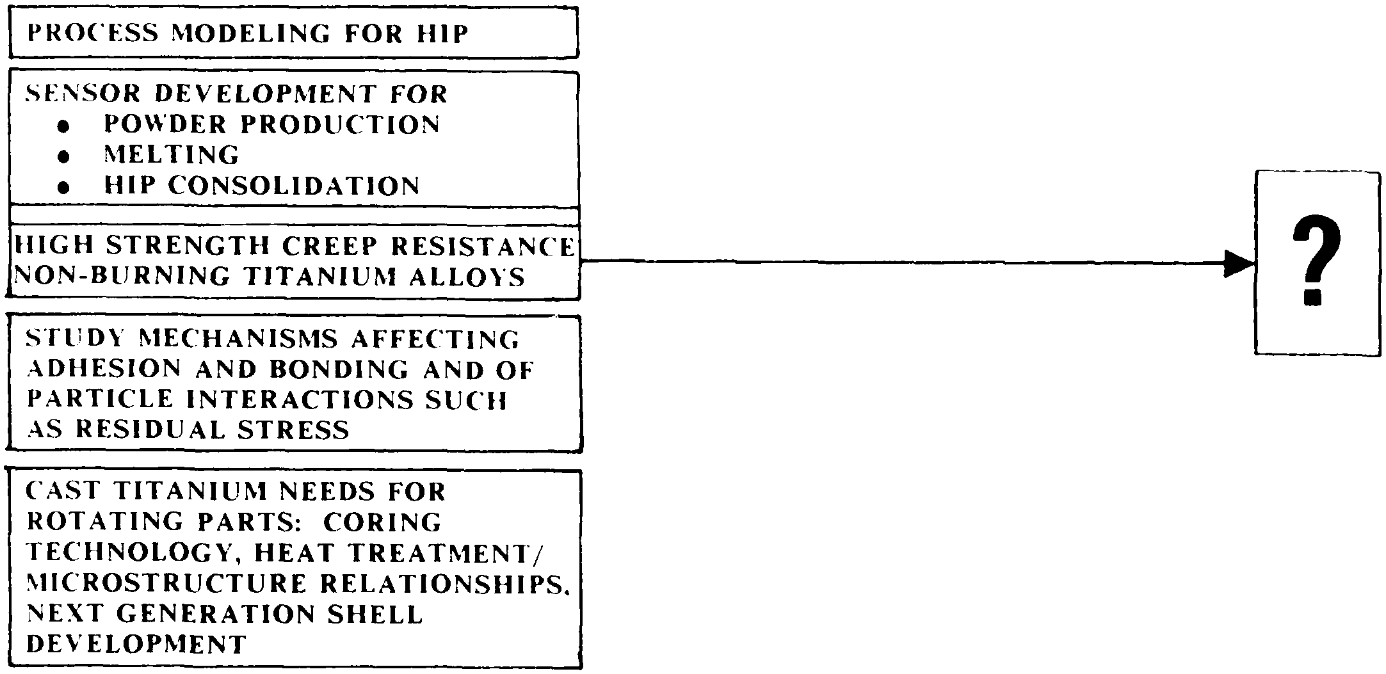
IMPROVE THE SUPPLY
OF DOMESTIC
CERAMIC POWDERS



This program is identified with the production of powders by domestic sources only, to establish a high quantity and consistent supply base.

*INJECTION MOLDING, SLIP CASTING, SOL GEL, REACTION BONDING HOT PRESS, SINTER, HIP

ROAD MAP 2-3 CERAMIC POWDERS



Candidates for road maps representing high-potential programs with expressed needs but without sufficient definition to qualify for programming.

ROAD MAP 2-4 CANDIDATE SUBJECTS: METALS

STATE OF THE ART - POWDER RESEARCH
POWDER DEVELOPMENT
POWDER PRODUCTION/
APPLICATIONS

MECHANISMS FOR IMPROVED TECHNOLOGY TRANSFER; IDENTIFY SUPPLY SOURCES

PROMOTE THE COORDINATION OF USEFUL INDUSTRY SPECIFICATIONS & STANDARDS

ORGANIZE POLICIES TO IMPROVE AN EXPANDED RANGE & VOLUME OF APPLIED COMMERCIAL PRODUCTS IN NEW TECHNOLOGY

INTEGRATED & INTERDISCIPLINARY SYSTEM FOR POWDER PRODUCTS

This program establishes a technology awareness effort to monitor and evaluate new developments in powder production and consolidation. It involves specialists from disciplines such as ceramics, chemical engineering, metallurgy, and mechanical engineering. The effort will provide recommendations for appropriate research, development, and application programs.

ROAD MAP 2-5 RECOMMENDED INSTITUTIONAL RELATIONSHIPS FOR POWDER MATERIALS

WORKSHOP 2 SPEAKERS[a]

1. Bridenbaugh, Peter. Roadblocks and Opportunities for High-Performance Powder-Metallurgy Aluminium Alloys.

2. Sprague, R. A. Superalloy Powder Processing for Critical Aerospace Applications

3. Cox, Art. Powder Metal Technology - Impact on Gas Turbine Net Shape Fabrication.

4. Ping, Stephen W. Consolidation Processing of Aluminum Powder Metal Alloys.

5. Richerson, David W. Structure-Property-Processing Relationships to Net-Shape Forming of Ceramics.

6. Mangels, John A. Net Shape Forming of Ceramics for High Technology Applications.

7. Smith, P. C. Some Emerging Net Shape Fabrication Techniques at GTE.

8. Prewo, Karl M. Forming Ceramic-Ceramic Composites.

   Prewo, Karl M. Ceramic and Carbon Fiber Reinforced Glasses

9. Bunshah, R. F. Overview of Coating Technologies for Large-Scale Metallurgical, Optical, and Electronic Applications.

10. Brown, S. D. Anodic Spark Deposition of Ceramic Coatings.

11. Hill, Russell J. Research and Development in Line of Sight Processes: Advances in Processing Large and Irregular Geometrics.

    Chang, Ping Y. Enhanced Magnetron Sputtering of Planarized Silica Coatings

    Evans, A. G., G. B. Crumley, and E. Demeray. On the Mechanical Behavior of Brittle Coatings and Layers

12. Mehrabian, Robert. Status of Powder Metals Processing - Future Research, Development, and Engineering.

13. Seraphin, B. O. Morphology, Composition, and the Optical Properties of Thin Films Deposited from the Vapor Phase.

14. Rockett, A. A. Thin Film Deposition by Plasma-Based Techniques.

15. Hecht, R. J. Coating of Net Shape Parts for Gas Turbine Propulsion Systems.

16. Schuster, David M. Cast Discontinuously Reinforced SIC-Al.

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[a] The material submitted for publication by these speakers appears in Volume III of this report.

17. Dulis, E. J. Near-Net Shape Process Using HIP of Alloy Powder Particles.

18. Lherbier, Louis W. Consolidation by Atmospheric Pressure.

19. Ghosh, A. K., and C. H. Hamilton. Superplastic Forming and Diffusion Bonding of Titanium Alloys.

Ghosh, A. K. Superplasticity in High Strength Aluminum Alloys.

Ghosh, A. K., and C. H. Hamilton. Influences of Material Parameters and Microstructure on Superplastic Forming.

20. Weisert, Edward D. The Realization of SPF/DB as a Commercial Fabrication Process.

Weisert, Edward D. The Nature of an Emerging Fabrication Technology, SPF/DB and its Quality Assurance Implications.

Weisert, Edward D. Advanced Structural Components by SPF/DB Processing.

21. Muzyka, Donald R. Do It Right the First Time.!

22. Ledger, A. Activated Processes at OCLI.

SECTION 3: COMPOSITE MATERIALS MANUFACTURING TECHNOLOGY

Composite materials are widely used - examples include automobile body panels and reinforced concrete - but with few exceptions they are still emerging as high-performance materials for aerospace applications. Still, military missions impose demands that point to steadily growing use of composites in aerospace structures. To permit designers to take full advantage of their capabilities, manufacturing technology for these materials must be improved significantly. Especially needed are improvements in automation and quality control, including the associated methods of NDE. The elements of the overall problem considered in this section are shown in Figure 3-1.

A military perspective on composite materials was provided at the committee's workshop on the topic by keynote speaker, Jerome Persh of DoD. He said in part, "It is certainly clear that the demands of the military, whether they be in land, sea, or air vehicles; ordnance, support equipment and so on, are such that composite materials will see an ever increasing role in achieving the capability to meet those demands . . . . They do much more than conventional materials. The price to be paid for them doing so much more is the need to assure that they precisely meet the design requirements set out for them. The only way to find out whether they will meet these requirements is through very sophisticated inspection techniques at each and every step along the way to the final product."

NATURE OF COMPOSITES

Composite materials are combinations of two (or more) organic or inorganic materials. One material serves as a matrix; the other serves as a reinforcement in the form of fibers, whiskers, or particles dispersed in the matrix in an appropriate pattern. The primary function of the matrix is to transfer stress to the reinforcing material. The reinforcement significantly improves the properties of the matrix material. These properties are tailorable; the composite may be designed to improve properties such as strength or stiffness or both, resistance to impact and creep, resistance to heat or other environmental factors, and dimensional stability. In addition, many composite materials have very low density, which can provide significant weight savings compared to conventional aerospace materials such as aluminum and titanium.

AEROSPACE APPLICATIONS

Composites in use or in development for aerospace applications comprise three broad groups: organic matrix, metal matrix, and ceramic matrix materials. The organic matrices include both thermosetting and thermoplastic polymers. The metal matrices are mainly aluminum and titanium alloys. Ceramic matrices include glass, silicon carbide, and silicon nitride. Carbon matrices are also classified in this group. Reinforcements for these matrices, as noted above, may be fibers, whiskers, or particles; the materials used include graphite, boron, glass, aramid, alumina, silicon carbide, and silicon nitride. The variety of fiber matrix combinations and their useful temperature ranges are listed in Table 3-1.

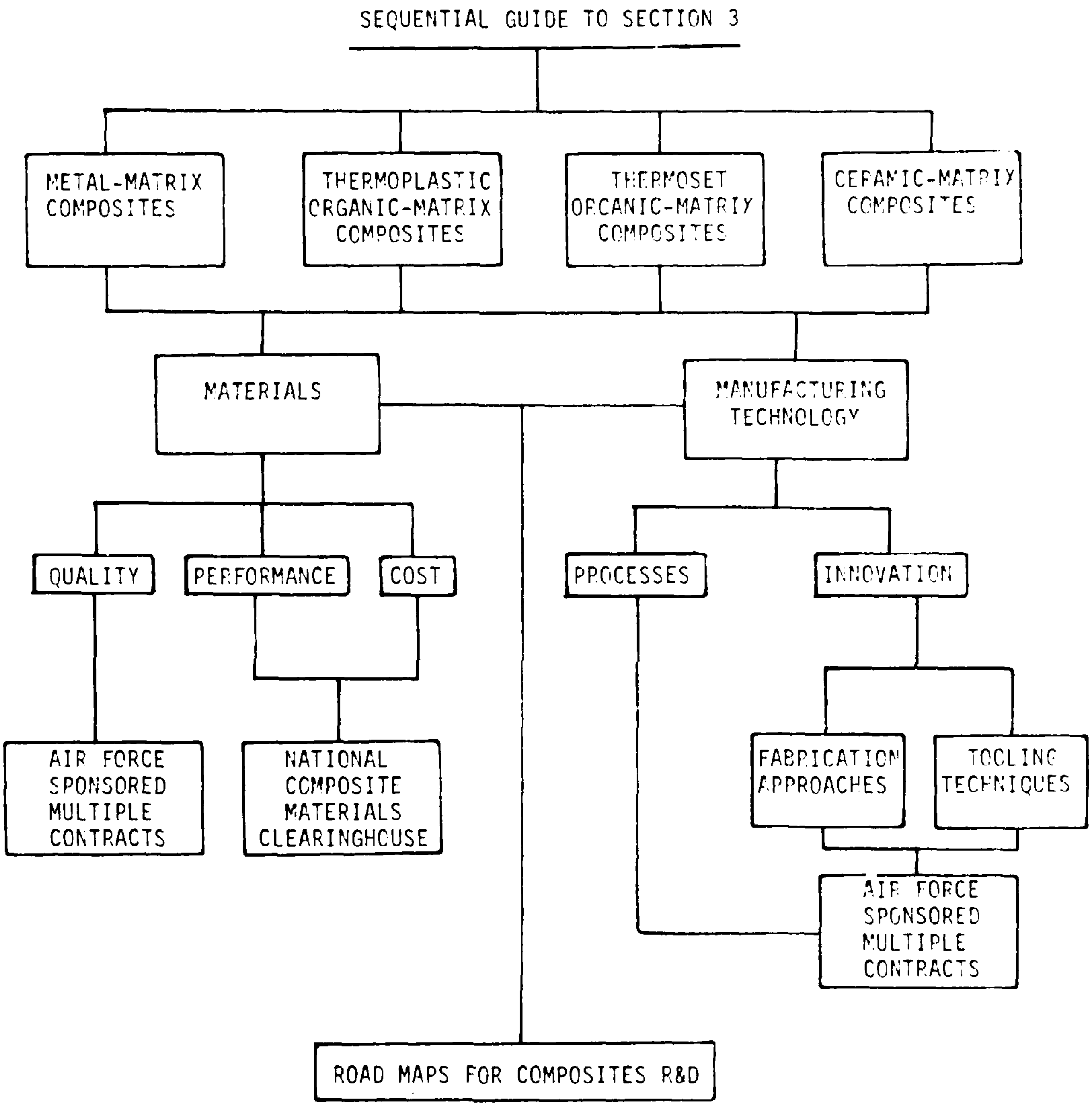

SEQUENTIAL GUIDE TO SECTION 3
METAL-MATRIX COMPOSITES
THERMOPLASTIC ORGANIC-MATRIX COMPOSITES
THERMOSET ORGANIC-MATRIX COMPOSITES
CERAMIC-MATRIX COMPOSITES
MATERIALS
MANUFACTURING TECHNOLOGY
QUALITY
PERFORMANCE
COST
PROCESSES
INNOVATION
AIR FORCE SPONSORED MULTIPLE CONTRACTS
NATIONAL COMPOSITE MATERIALS CLEARINGHOUSE
FABRICATION APPROACHES
TOOLING TECHNIQUES
AIR FORCE SPONSORED MULTIPLE CONTRACTS
ROAD MAPS FOR COMPOSITES R&D

FIGURE 3-1

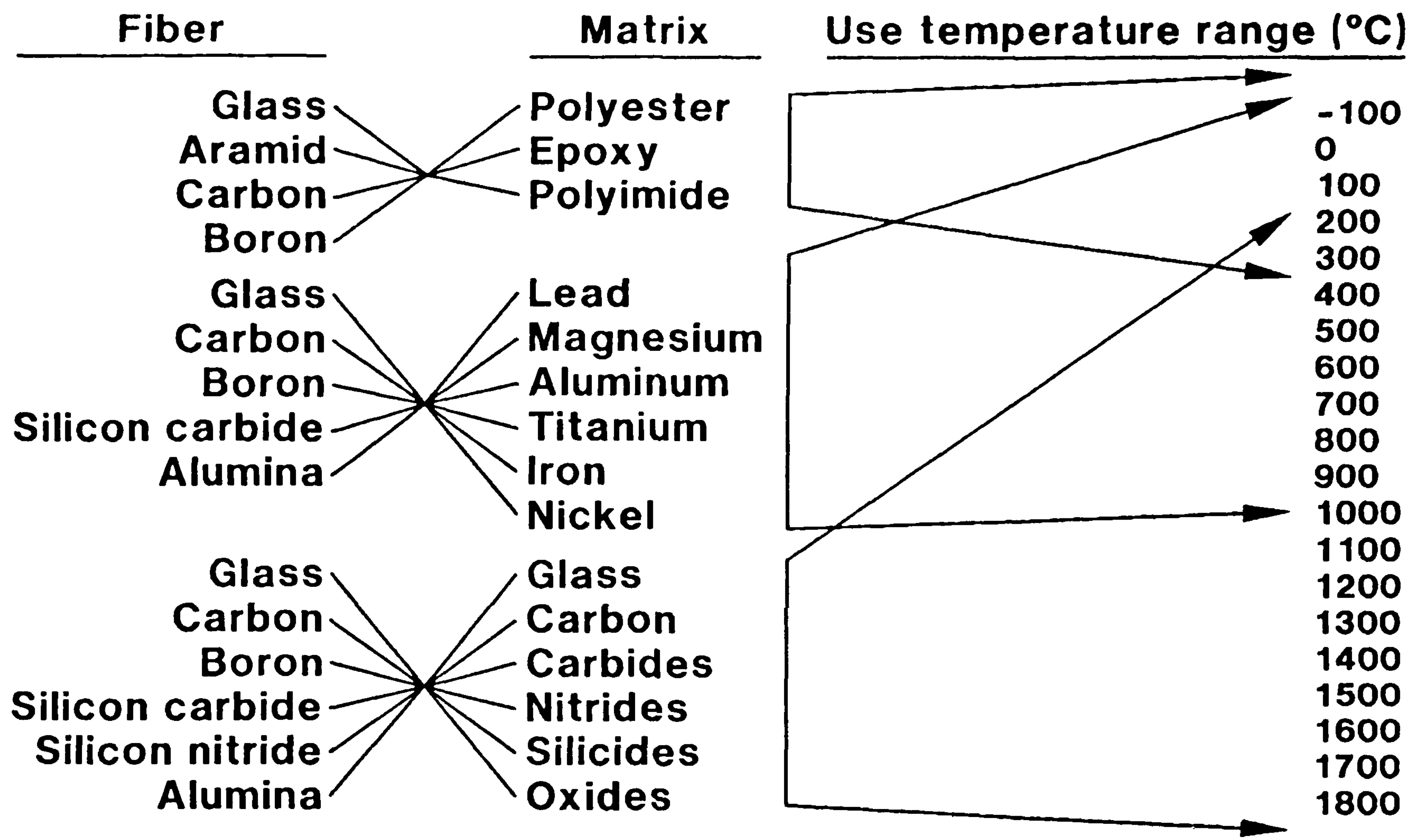


TABLE 3-1 USEFUL TEMPERATURE RANGES FOR VARIOUS TYPES OF REINFORCED COMPOSITES

Source: Prewo, K. M., United Technologies Research Center

During the past 25 years the use of high-performance composites on U.S.-made fighter and attack aircraft has climbed from one or two percent to 28% of airframe structural weight (Figure 3-2). The percentage is lower on heavier aircraft, but the absolute amounts can be substantial. Composites make up only 2.3 percent of the structural weight of the B-1B, for example, but total 6,600 pounds per aircraft. Requirements for the next generation of Air Force fighter, the Advanced Tactical Fighter (ATF), are expected to push composites to between 40 and 50 percent of structural weight.

Current and future applications of composite materials include aircraft, missile, and space structures and engines. These applications and potential temperature capabilities of the materials are shown in Figure 3-3. The composites on U.S. military aircraft now in service are thermosetting resins, mainly epoxies, reinforced principally with graphite fibers, but also with glass, aramid, and boron fibers. Airframe prices and material costs are shown in Figure 3-4.

As Figure 3-4 shows, the price per pound of airframe (complete aircraft less engines and avionics) varies considerably, even given the uncertainties inherent in such compilations of data. Depending on the type of aircraft, these prices range from a high of about $750 per pound for fighter and attack aircraft to a low of about $20 per pound for light single-engine aircraft. The escalating costs of airframes, especially for fighter aircraft, are a major concern. In dollars per pound, these costs have tripled since 1950 (Figure 3-5).

The flyaway costs (total procured costs including scrap and waste) of airframe materials also vary considerably. Aluminum may cost as little as $5.00 per pound whereas boron epoxy can be as much as $350 per pound. Manufacturing and quality assurance costs must be added to these material costs.

At current prices, and even with the significant (20-30%) weight savings that have been demonstrated, the primary cost-effective and affordable use of composites will be in large transports, business jets, turboprops, and future fighter and attack aircraft. In addition, automated manufacturing techniques must be employed to reduce manufacturing costs.

One of the major advantages of composite structures is the ability to tailor the component to a net shape where, because of the stiffness and strength, and the ability to co-cure, many fewer parts are needed to satisfy the structural requirements of a number of built-up structural components. Therefore, although material and fabrication costs may be higher, because of reduced part count, the installed cost of the component could be lower than for comparable built-up and assembled structures of aluminum.

The ATF and comparable aircraft will require improved composites for structures and engines. Candidates for use in airframes include advanced organic matrix composites based on epoxy and other thermosetting resins, thermoplastic resins, and metal matrix composites. Engine applications offer opportunities for organic matrix as well as metal and ceramic matrix composites.

Production uses of metal and ceramic matrix composites in aerospace applications are few. Boron aluminum parts are used on the space shuttle and graphite aluminum parts on the space telescope. Forgings of aluminum reinforced with silicon carbide particles are scheduled for production in 1986 for use on

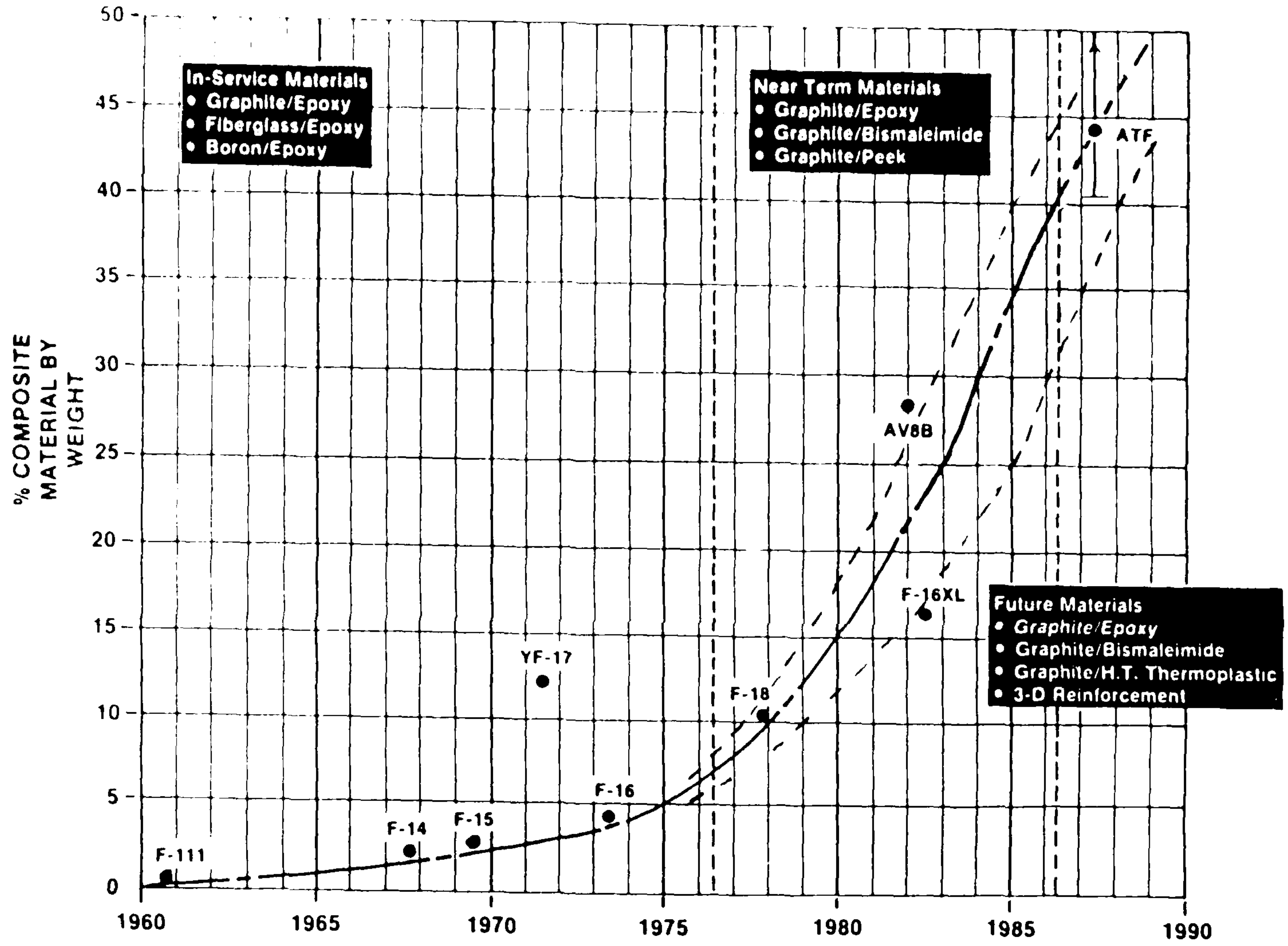


FIGURE 3-2 COMPOSITE MATERIAL UTILIZATION TREND

Source: Stout, R. J., General Dynamics Corporation

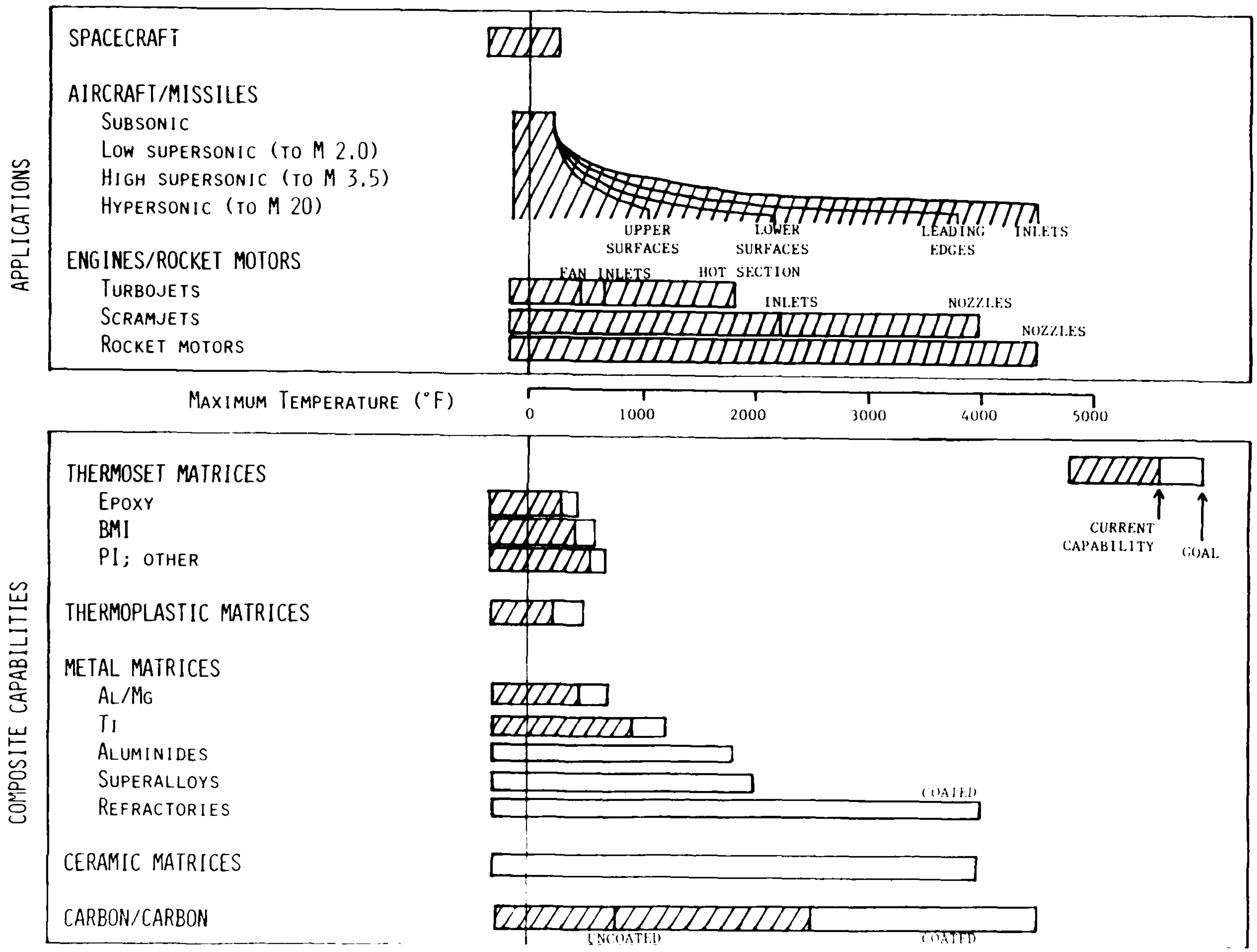
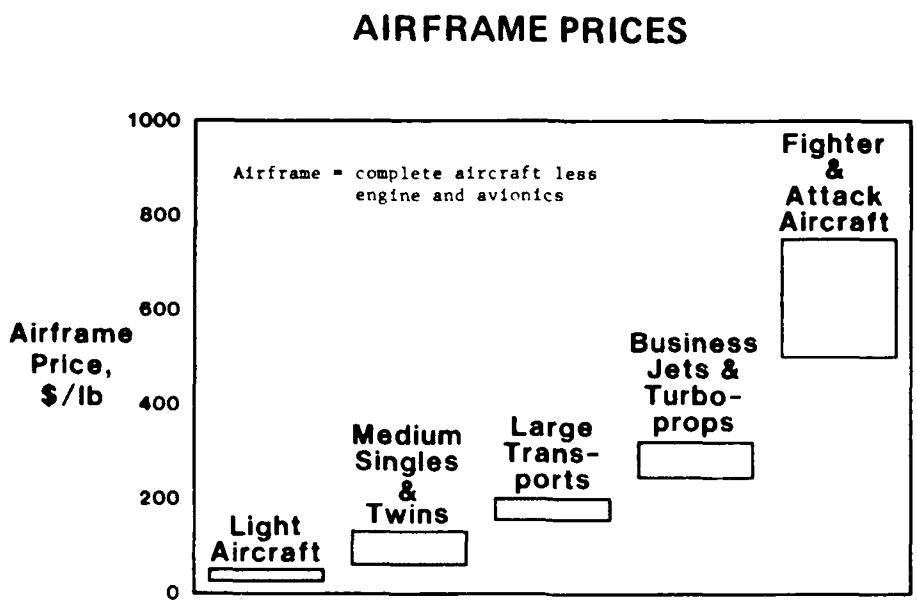


FIGURE 3-3 STRUCTURAL MATERIAL APPLICATIONS AND CAPABILITIES



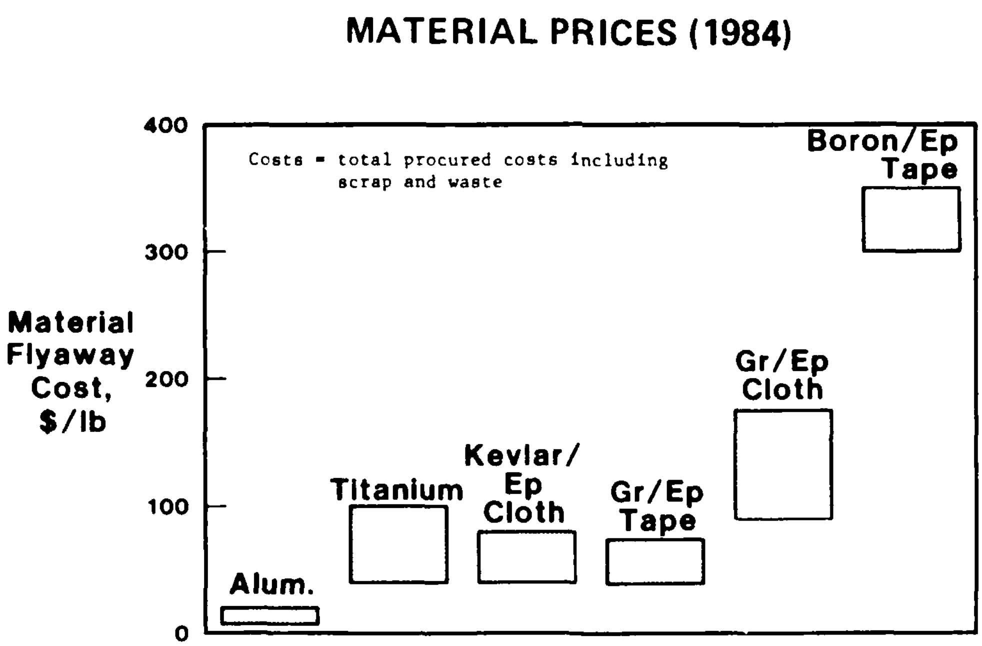


FIGURE 3-4 PRICES FOR MATERIALS AND AIRFRAMES

Source: Hadcock, R. N., "Composite Airframe Production Implementation," presented at AIAA Aerospace Conference & Technical Show, February 12-15, 1985.

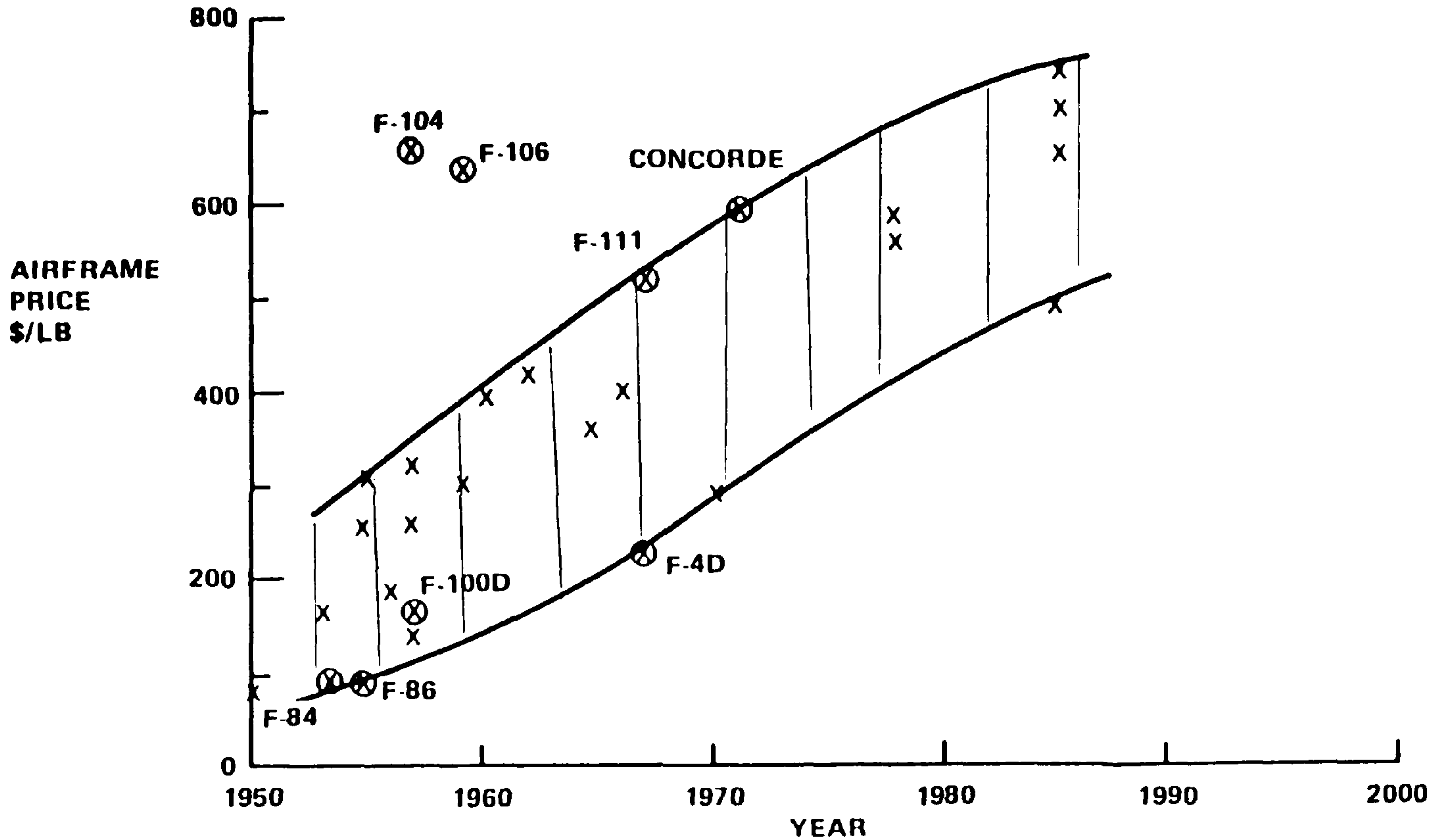


FIGURE 3-5 AIRFRAME PRICES: HIGH PERFORMANCE AIRCRAFT
(CONSTANT 1985 DOLLARS)

Source: Hadcock, R. N., "Status and Viability of Composite Materials for High Performance Aircraft," presentation to Aeronautics and Space Engineering Board (National Research Council), Feb. 10, 1986, Monterey, California.

the Trident missile. Aerospace use of ceramic matrix composites today is limited to carbon-carbon for reentry vehicle nose tips, rocket nozzles, the leading edge and nose cap on the space shuttle, and aircraft brakes.

THERMOSET ORGANIC MATRIX COMPOSITES

Shortcomings of Material

The graphite epoxy composites used for most aircraft applications today have several shortcomings. One is their relative brittleness, which takes the form of lack of ductility and degradation of compression strength following low-energy impact damage. Also, their sensitivity to moisture limits these composites to service temperatures below 260 ° F. Another shortcoming is the slow and costly processing of parts, which typically are cured in an autoclave at 350 ° F and 100 psi for one to two hours. This procedure entails a heat-up through cool-down cycle of up to eight hours.

A major problem associated with graphite epoxy composites is the quality of the prepreg used to make parts. Prepreg is a tape or cloth formed by impregnating fibers with resin that may be partly cured. The product is sticky and is backed by paper until ready for use. The airframe manufacturer procures prepreg and converts it to parts by stacking precut plies of the material, which are then usually cured in an autoclave.

Standardization of Material

Prepreg has major problems associated with quality, reproducibility, variations in thickness, and physical defects. These problems affect the manufacture of parts in several ways. Extensive inspection requirements in combination with rejection and rework raise costs. One manufacturer cites reject rates of up to 20% at times. Variability and poor quality of prepreg hamper automation, which is essential to improving both the consistency and affordability of composite parts made in reasonably large numbers. The shortcomimgs of prepreg also contribute to concerns about the quality, reliability, durability, and performance of parts, which affect design. Designers typically use only about 40% of the compression strain theoretically available in graphite epoxies. Caution in design additionally cuts into potential weight savings. Standardization of materials in the form of uniform, close tolerance specifications is needed now. Continued effort should be directed toward the development of less brittle, higher temperature resin systems.

Prepreg Quality

An example of the quality problem is the variable thickness of graphite-epoxy prepreg plies. Thickness depends on the weight of fiber per unit area, or fiber areal weight (FAW), and resin content. A typical ply has an FAW of 145 ± 5 g m^{-2} and a resin content of 35 ± 3% by weight. The ply cures to a thickness of about 0.005 in., so 100 plies are used to form a typical laminate with a nominal thickness of 0.50 in. The thickness of the cured laminate can vary within a tolerance of $\pm$ 0.05 in., and it is not practical to surface-mill the material. Such variations create problems with measuring thickness of parts, complexity of tooling, and inventories of fasteners of variable lengths required to accommodate variations in thickness. A manufacturer points out that variations in the thickness of the AV-8B composite wing skin add as much as 30% to the cost of assembly.

People in the industry believe that graphite epoxy prepreg tolerances could be tightened to an FAW of 145 ± 1 g m^{-2} and a resin content of 35 ± 1% or even ± 0.5%. Thickness tolerance for a 0.50 in. laminate would then be ± 0.015 in. at a resin content of 35 ± 1% and ± 0.009 in. at a resin content of 35 ± 0.5%. These tolerances would present no problem in making parts. The tolerance for resin content already has been reduced from ± 5 to ± 2%, so the FAW tolerance might be the best place to start.

Prepreg Characterization Specifications

Efficient production of high performance graphite epoxy components also would benefit from more thorough characterization and standardization of those properties of starting materials that affect manufacturability of parts. Prepreg suppliers, for example, typically cannot predict the cure and postcure behavior of their products. The user must determine the kinetics of curing and must be ever alert to the possibility that kinetic parameters may vary from batch to batch. A truly fundamental grasp of the chemical kinetics involved is probably unnecessary, however. Techniques are available for fingerprinting products using preselected standards. A profile by high-pressure liquid chromatography, for example, will detect variations in the composition of epoxy resins. In this vein, industrywide specifications for graphite/epoxy prepreg are being considered by a technical committee of the Suppliers of Advanced Composite Materials Association, a trade group formed in March 1985.

Automated Process Control/Sensor Development

Automatic process control and adjustment will be needed to produce graphite/epoxy prepreg with adequately low thickness tolerances. To achieve effective automated control, however, more must be known of the key parameters of the raw materials and process. Improvements in sensors will be needed as well. Sensors for FAW and resin content are used fairly widely, but we have no really good, validated sensors for parameters such as gel time and resin flow, nor is it clear how best to detect mechanical defects. One problem with obtaining improved sensors is that the market is too small to attract strong development efforts by instrument makers. An integrated sensor development program with industrywide participation and communication of needs and results would be well worth funding. Capital cost is not a major problem; most prepreg makers would be willing to install automated control equipment if it were available.

Advanced Curing Concepts

Various advanced concepts for curing thermoset resin composites have been examined with the goals of reducing costs and easing other problems with current methods. State-of-the-art methods today are the autoclave, vacuum bag - oven, and compression molding, and each has disadvantages. Autoclave equipment is expensive; compression molding requires expensive tooling and is not suitable for conventional prepregs.

Curing methods that may find use with aerospace parts in the future include nonautoclave curing (under vacuum in an oven); coldwall autoclave curing; pultrusion; radio frequency (RF) curing; elastic reservoir molding, a compression molding process; and electron beam irradiation. Some of these techniques are already in limited use or are used widely in other fields. Each requires development for aerospace work. RF curing, for example, was tried in the mid-1970s and seemed promising. The method may warrant renewed development because new RF techniques have since become available. Electron beam curing has good potential, but could be costly and poses many unanswered questions. The vacuum bag - oven method imposes limits on part geometry and thickness, and parts may have questionable mechanical properties.

Advanced methods of monitoring and controlling curing cycles have become available in recent years. Computer-aided autoclave control systems are on the market, and software for modeling curing cycles has been developed. Also, continuous monitoring of the dielectric properties of a resin while it is curing can be related to the physical state of cure. Current practice is to monitor temperature and pressure, which gives no information on the state of the resin. Demonstration that dielectric monitoring can accurately identify the completion of cure will significantly reduce autoclave time.

Development of advanced curing concepts does not entail particularly high cost. It thus appears that such work would best be funded by multiple, relatively small contracts.

Tooling Development

As organic matrix composite aerospace parts have become more complex, the size and complexity of tools have increased correspondingly. The cost of tools and the time required to make them have grown as well. In addition, several different tooling materials are being used. Metal tools are very durable and have good thermal conductivity, but they do not control critical dimensions well because of the mismatch between the coefficients of thermal expansion of the tool and part. Composite tools, on the other hand, provide good control of dimensions and contours, but suffer from low thermal conductivity, poor durability, and high maintenance and repair costs.

Tooling materials pose a mix of problems that must be solved to reduce costs. Further, tooling systems must be modernized to be compatible with CAD/CAM. Computer generated designs of composite structures can be used directly to machine the master model, the permanent pattern, or the layup mold tool itself. Since the technology exists, new tooling materials and systems should be evaluated with it in mind.

Work in these areas is in its first year at Fairchild Republic under an Air Force funded program. The company will evaluate new tooling concepts for curing graphite/epoxy at 350 ° F. At least three materials/systems will be selected from 15 or more candidates. One material/system will be fabricated for each of three generic types of composite structures - internal, external, and co-cured - and will be subjected to thermal cycling tests. Finally, a full-scale tooling system will be evaluated through several autoclave cycles at 350 ° F. A composite part 6 to 10 feet long is being considered for this demonstration.

Standardization of Material Systems

We see an urgent need to standardize material systems that have become sufficiently mature to be selected for use in production programs. The objective of such an effort would be to develop standardized classes of composite systems that would be fully qualified and also would have an extensive data base of physical properties and design allowables. The tasks involved would include development of uniform material and processing specifications and standards as well as qualification procedures and test requirements. A standardization program of this kind could be the responsibility of a federal laboratory or other organization selected by DoD as a National Center. The objectives and payoffs of this approach are outlined in Table 3-2.

Skilled Manpower

A critical need in composites is manpower skilled in manufacturing and processing the materials. A significant increase in aerospace usage of composites would require additional trained personnel, and no comprehensive plan exists for obtaining them. Available vehicles include DoD Tech Mod programs and some initiatives of the Air Force Aeronautical Systems Division. In addition, the Air Force could sponsor faculty positions at leading colleges and universities across the United States to help provide the specialized education and training needed in composites manufacturing and processing.

Higher Temperature Organic Matrices

Epoxy resins are unsuitable for long use above 260 ° F. Two other thermosetting resins, bismaleimide (BMI) and polyimides (PI), are used in organic matrix composites for such applications. BMI is suitable for service at up to 400 ° F and PI at up to 550 ° F. However, processing requirements for polyimides are more demanding than for epoxy or BMI (600 ° F/200 psi vs 350° F/100 psi), which raises costs significantly. Lower curing temperatures for both BMI and PI, and more readily processible PI, should be achievable, however, and development in these areas is under way. These resins cost far more than epoxies, and composites made from them are more brittle at room temperature than their epoxy counterparts.

THERMOPLASTIC ORGANIC MATRIX COMPOSITES

A strong effort is under way to develop thermoplastic resin matrices for advanced composite materials, but no structural parts made of these materials are yet flying. Representative examples of major thermoplastic systems under development are shown in Table 3-3.

Conventional and thermosetting thermoplastics show great promise. Several thermoplastic resin polymers have much higher interlaminer fracture toughness than expoxies. Thermoforming principles are well established for resins with lower glass transition temperatures (Tg), but more work is needed on higher Tg systems. The processing of newer resins should be improved. Yet to be shown are the feasibility of producing large, flat (thermoformable) sheet and clear economic advantages of using such materials. The thermoplastics also pose specific critical questions. What is the best way to make flat sheet for ther-

- OBJECTIVE

  DoD shall require materials to be qualified to uniform standards.

- DIFFERENT CLASSES OF MATERIALS
  - fibers
  - matrices
  - adhesives
  - coatings, etc.

- STANDARD MATERIAL CLASSES
  - material specification/standards
  - processing specifications/quality control
  - tooling specifications
  - qualification procedures/tests

- RESPONSIBILITY

  NBS or other appropriate government laboratory

- PAYOFFS
  - opens up competition
  - reduces material, qualification, manufacturing costs
  - cuts time for product/process improvement
  - enhances data base
  - reduces risk

TABLE 3-2 STANDARDIZATION OF COMPOSITE MATERIALS

Type	Chemical Classification	Examples
Semicrystalline	Polyetheretherketone	PEEK (ICI)
	Polyphenylene sulfide	"Ryton" (Phillips)
Amorphous	Polyamideimide	"Torlon" (Amoco)
	Polysulfone	"Udel" (Union Carbide)
	Polyethersulfone	"Victrex" (ICI)
	Polyimide	"Ultem" (GE)
		LARC TPI (NASA)
		"Avimid" K-II (Du Pont)
Liquid crystal	Polyester	"Xydar" (Dartco)
		"Vectra" (Celanese)

TABLE 3-3 TYPES OF THERMOPLASTICS

Source: Gibbs, H. H., E.I. Du Pont De Nemours & Co.

moforming? What matrix melt viscosities are needed for economic feasibility? Can the degree of crystallinity be properly controlled? Is the present method of measuring solvent resistance good enough? Will it be possible to make large, complex parts of graphite thermoplastic? And do the potential economic returns justify the high development costs?

Advantages and Shortcomings

The toughness of thermoplastic composites allows designers to use higher strains than are possible with the epoxies and other thermosets in use today, and thermoplastics also are far more tolerant of impact damage. Designers could thus take fuller advantage of the higher strain graphite fibers that have become available during the past few years. However, resistance to solvents has been a problem with some thermoplastic materials. Also, the cost of thermoplastics - currently $100 to $200 per pound - is significantly higher than the cost of comparable thermosets.

Processing techniques for preconsolidated sheets of graphite/thermoplastic include hot-head tape laydown, autoclaving, matched die molding, and a pultrusion/extrusion process. The materials would be used more widely if they could be handled in tape-laying machines. Some thermoplastic resins, such as PEEK, are available in many forms, including film, tape, co-woven fabric, standard fabric, and tubes. Forming processes include brake forming, pultrusion/extrusion, hothead layup, matched metal die molding, roll forming, thermoforming, hydroforming, and hydraforming. Potential applications of thermoplastic-matrix composites include wing skins, stiffeners, control surfaces, [illegible] panels and doors, brackets, fairings, and other secondary structures. [illegible] areas in addition to those noted above include costly facilities, [illegible] viscoelastic behavior, and the need to adapt design, analysis, and [illegible] methods to new materials. Self-heated tools or an autoclave [illegible] are needed; the layup would be heated in an oven before transfer [illegible] or shaping machines or both.

[illegible] major problem is the fatigue and creep behavior of thermoplastic [illegible] particularly at high temperature. The necessary tests are time [illegible] costly and are not normally conducted early in the development [illegible] the fatigue and creep performance of the thermoplastics now in [illegible] uncertain.

[illegible] be expected in the properties and processibility of the [illegible] under study, given their early stage of development. [illegible], however, which seriously hampers the develop- [illegible] manufacturing database. Basic design data are [illegible]. Secondary structural applications should be [illegible] and confidence in the materials. Also [illegible] commitments to proceed with test programs for

[illegible] PRODUCTION
[illegible] MATRIX COMPONENTS

[illegible] high performance organic matrix com- [illegible] These remarks pertain to epoxy matrix parts; the principles, however, extend to other thermoset resins and thermoplastic resins, although specific problems may differ.) Cost-cutting possibilities include automated fabrication, new concepts in tooling and curing, better methods of joining, and improvements in NDE of components. The privately and government funded development work under way in these areas is well justified.

Perspective on manufacturing costs is provided by Figure 3-4. The flyaway price of airframes for fighter and attack aircraft ranges from about $500 to $750 per pound, whereas the flyaway cost of graphite epoxy, the most widely used composite material, ranges from about $50 to nearly $200 per pound, not including the cost of manufacturing and assembly. Substantial reductions must be made in the cost of manufacture and assembly of composite parts using automation. The saving that automation might actually achieve, however, is uncertain at its present state of development.

Design-Manufacturing Integration

Efficiency in manufacturing benefits from vertical integration of people and information, but it must be done early in a program to achieve maximum savings. Computers are powerful, if initially costly, tools for implementing such integration. Experience with making composite parts has demonstrated the value of vertically integrating and colocating all functions, from design through manufacturing. This arrangement facilitates additional beneficial measures, including regular meetings of key personnel, minimizing the number of approvals required to take action, and making full use of computer-integrated manufacturing (e.g., interaction of CAD and CAM functions).

Design-manufacturing integration is difficult to achieve because of the institutional, technical, and informational barriers that must be overcome. Technical barriers include problems associated with designing for automated fabrication when the capabilities or limitations of the automated facilities are either undefined or very loosely defined. Problems equally exist from the viewpoints of manufacturing and quality assurance where it is impossible to define the details and needs of the automated facility before the design is defined in detail together with all the requirements such as part descriptions, dimensional tolerances, and attachment details. A [illegible] design handbooks, which are too numerous and often [illegible]. More compact storage of design information is needed [illegible] viceability and programs on computer-aided design [illegible] components.

Several automated fabrication techniques [illegible] coming after the fact [illegible] designed originally [illegible] niques. Second-generation [illegible] cation using these [illegible] reflected in the design [illegible] developing techn[illegible] danger is that [illegible] develop unique engineering [illegible] severely [illegible] the acquisition [illegible]

Automated Fabrication

Automated fabrication of epoxy matrix composites is needed, as noted earlier, both to reduce the cost and improve the consistency of parts. Automation is best suited to high-volume production. Even where volume is low, however, automation should yield substantial savings if it is designed to be flexible.

Fabrication costs are high because of high labor requirements combined with the variability and inadequate quality of prepreg. The characteristics of prepreg also complicate mechanical handling. Extreme care is needed to avoid damage and insure that there are no foreign objects between plies.

Other characteristics of prepreg also hamper automation. A company developing a prepreg tape-laying machine reports a variation in the width of 3-inch tape. Also, the tape will not naturally run straight over surfaces that have double curvature. These conditions make it difficult, if not impossible, to control gaps between adjacent lengths of tape as it is laid down. One solution to this problem, cited by an airframe company, is to recognize that the tape "has a mind of its own" and use "natural-path" programming on the tape-laying machine and accept gaps at less critical points in the laid-down material. Other solutions include machine layup of narrow tape or use of forms of composite other than prepreg tape or broadgoods.

Alternative Methods of Fabrication

Several alternatives to prepreg layup are available or are being developed. They include filament winding, pultrusion, injection molding, and press molding.

Filament Winding

Filament winding has been used successfully for many years to fabricate [illegible] rocket motor cases, cylindrical struts, and similar structures. It is a fast and efficient way to lay up large amounts of material. Aerospace components [illegible] are filament wound using narrow prepreg tape or by winding tows [illegible] that are impregnated by running them through uncured resin just [illegible] winding. Numerically controlled filament winding machines and new kinds [illegible] wind entire fuselages or missile bodies [illegible] no longer limited to cylindrical components.

[illegible]

forcements used today are glass, graphite, or aramid fibers in unidirectional or multidirectional forms (woven fabrics, stitched fabrics, mats).

Pultrusions are highly controllable, reproducible, and, relative to other aerospace composites, affordable. The major inhibitor is that the process can be used only to make straight, constant cross-section parts, such as tubes or hat or I-section stiffeners, which cannot easily be formed to curved shapes.

Continuing evaluation and monitoring of the development of pultrusion technology are highly desirable. Specific future applications would take the form of stiffeners for wing or fuselage covers of large transport aircraft, the shells of missile structures, or tubular parts of large space structures.

Injection Molding

Injection molding consists of placing a stitched preform of the reinforcement material into a closed die and injecting liquid resin into the die. The resin is then heat cured. Injection molding is limited to detail parts, but is a very effective way to make highly curved or complex-shaped parts to net shape. Continued funding of technology development is warranted in this area, where special techniques and resins must be used.

Automated Fabrication and Assembly

Several methods of automated fabrication of composites are being developed and implemented. One method is the Automated Ply Laminating System (APLS) being developed by McDonnell Douglas with Navy support. APLS will be coupled with an Integrated Composites Center; the goal is to demonstrate full integration of composite shop-floor operations with computer integrated manufacturing, planning, scheduling, and control. APLS is designed to automatically handle random ply shapes cut from graphite epoxy broadgoods, from ply cutting through ply sorting and lamination (Figure 3-6). The system is scheduled for production in 1988. It is modular and will be adaptable to various manufacturing sites.

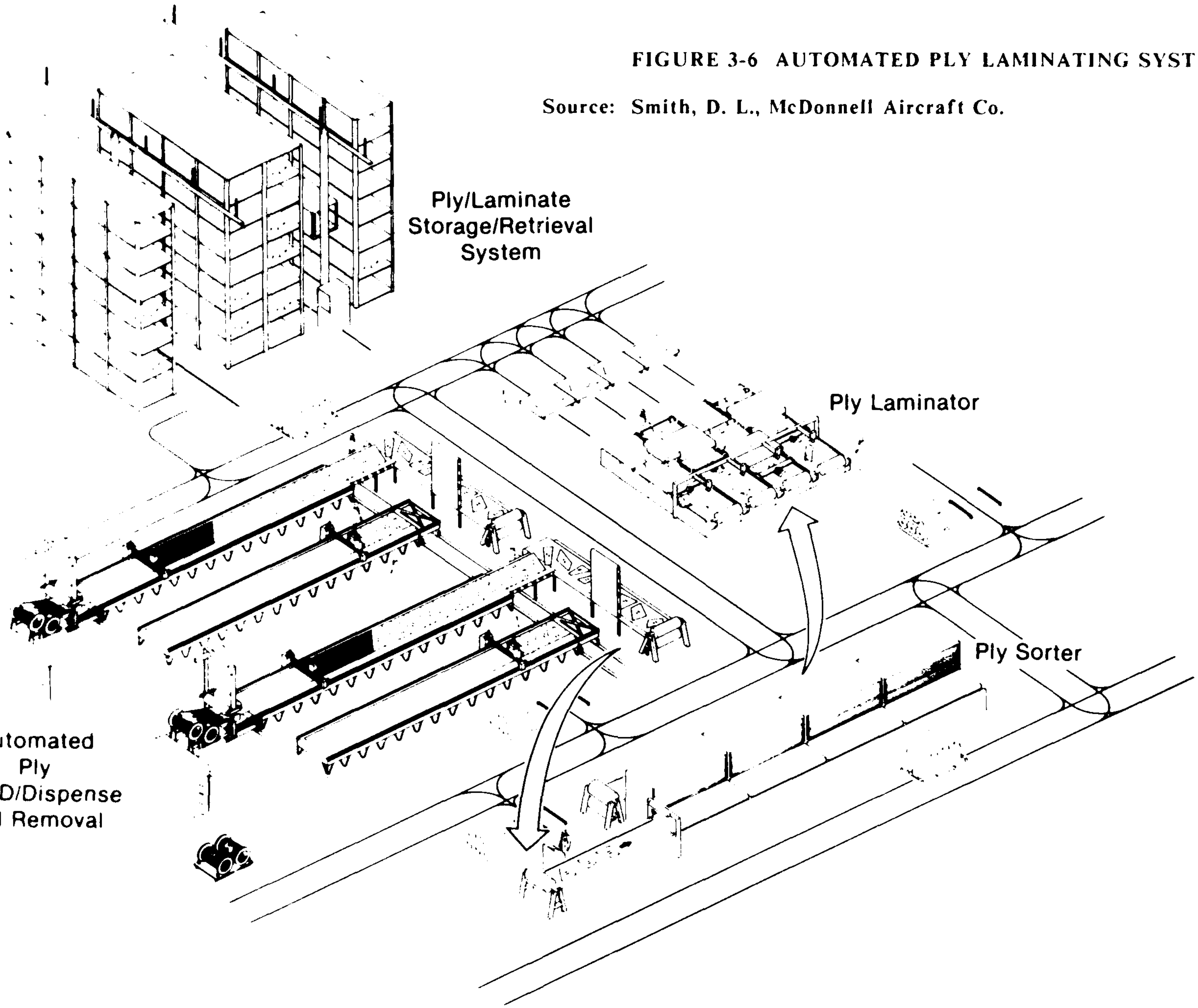
Another example of automation is the Automated Integrated Manufacturing System (AIMS) developed by Grumman with Air Force support. AIMS was developed to demonstrate a very flexible approach that could be used to fabricate parts of simple or complex shape. The system includes a tape-laying machine, NC ply cutting, and automated ply stacking. AIMS also includes an NC stitching capability.

A third example is the system developed by Northrop with Air Force support. The system employs overhead transfer equipment and robots to stack precut plies (Figure 3-7).

All three companies have extended their development of automation [illegible] McDonnell Douglas [illegible] Grumman [illegible]

FIGURE 3-6 AUTOMATED PLY LAMINATING SYSTEM

Source: Smith, D. L., McDonnell Aircraft Co.



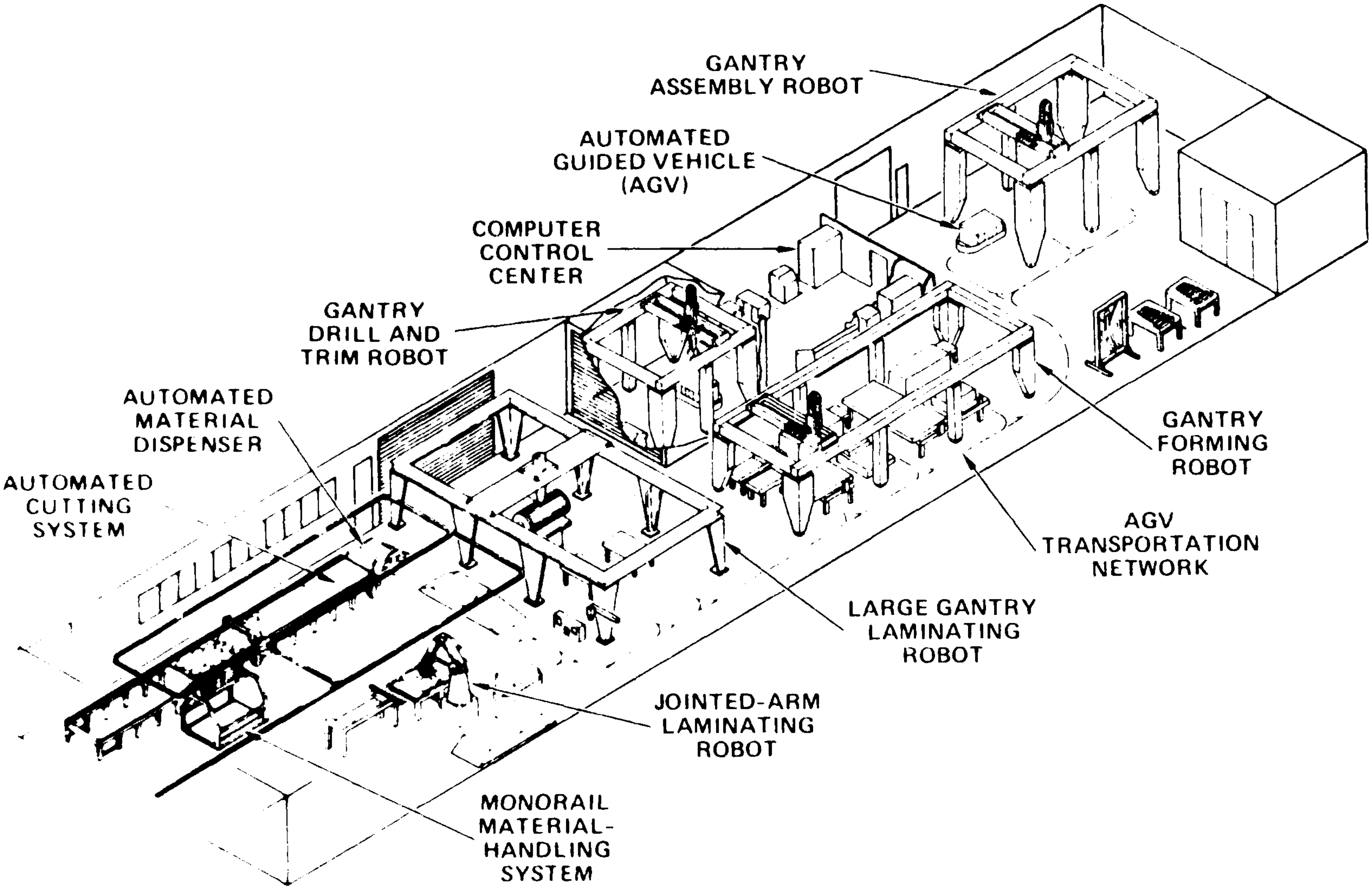


FIGURE 3-7 AUTOMATED COMPOSITES CENTER (ACC)

Source: Hall, T. F. W., Northrop Corporation inspecting them for diameter and roundness, installing the fasteners, machining the fastener heads, and inspecting them for flushness. Figure 3-8 shows the projected impact on costs of the automated pre- and postcure procedures at Grumman. Equipment is being fabricated for the assembly cell (and forming cell) of the four-cell Northrop system; the other cells are operational, and the facility is scheduled to be fully operational by the end of 1986.

Although much has been done and demonstrated, several issues must be resolved to take full advantage of automation. These include:

- Confidence in unmanned operation
  - -- system standardization
  - -- system integration
  - -- intelligent sensing and control
- Start-up and supporting costs
  - -- tools and fixtures
  - -- software
  - -- data availability
- Quality control
  - -- in-process control
- Engineering, manufacturing, and quality
  - -- design for automation

Sensor Development

Progress toward automated fabrication depends on developments in sensor and video camera technology. Such technology will be necessary to achieve in-process quality control by assuring that all parts of the fabrication system operate continuously within the programmed parameters.

Quality Assurance

Much progress has been made in recent years in automation and the use of computers in quality assurance of organic matrix composite parts. The emphasis is shifting now to continuous monitoring and inspection from the earliest design phase through the entire manufacturing process. The purpose is to identify and eliminate faults at the earliest possible point - the point of least value added - in the process. This approach will be particularly important in automated manufacturing.

Inspection techniques have not kept pace with this trend. Automation requires improved NDE methods such as ultrasonic and X-ray scanning. Current methods detect flaws and voids in composite-composite bonds, but give no reasonable estimate of bond strength. Earlier efforts to make ultrasonic and X-ray [illegible] automation did not succeed. Nuclear magnetic resonance spe[illegible] but has received little development effort. [illegible] Aerospace Industries Association is starting a cooperative R&D program on characterization and NDE of composites.

[illegible] rejected parts has become a serious problem. A major [illegible] reports that parts rejected by NDE are often delayed [illegible] 6 weeks [illegible]. Rejected parts must be analyzed for the [illegible] made to repair or scrap and the method

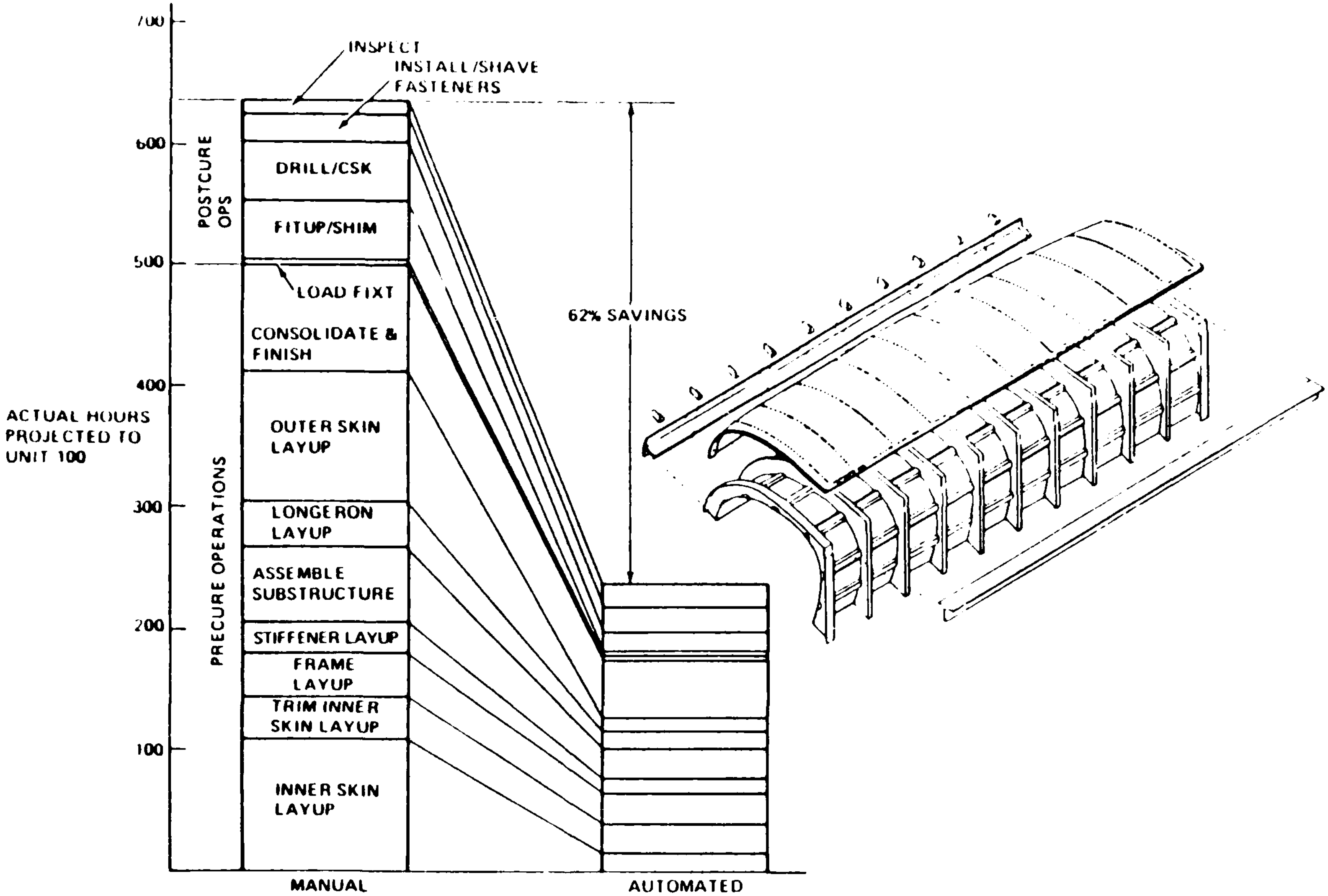


FIGURE 3-8 MANUAL/AUTOMATED COMPOSITE FABRICATION COSTS

Source: Marx, W., Grumman Aerospace Corporation of repair detailed and implemented. One of the difficulties is the absence of standards for the effects of specific types of flaws on the integrity of the part. The problem would be eased significantly by the development of guidelines for assessing and repairing manufacturing defects on the basis of statistically meaningful test data. Such data could be collected and analyzed using a round-robin approach for exchange of industry information. A program addressing the reject problem is urgently needed.

Composite Joints

Traditional methods of joining composites were adapted from sheet metal technology, which has influenced the shapes of composite parts, the drilling of holes, and the types of metal fasteners used. Drilling is more costly with composites than with metals, and fasteners may cost as much as $10.00 each. Interference-fit holes weaken composites. Fasteners will remain in use, however, and designs are needed that are less costly and are tolerant of variations in the thickness of composite laminates.

One reason for the continuing use of metal fasteners is the inability to assess the strength of composite-composite bonds with confidence using current NDE techniques. Nevertheless, a trend is developing toward cocuring composite parts to form larger, bonded components. This approach as now practiced creates problems of its own, and it appears that further development of new joining technology, such as stitching, is warranted.

DAMAGE REPAIR

Future military aircraft will require improved maintenance and repair procedures for composites. A particular concern is repair of battle damage, which should be completed in 1-2 hours. Routine peacetime repairs, in contrast, are normally completed within 8 hours. Advanced spacecraft also will use composites to a considerable extent and repairing them in space presents special problems.

Current procedures for repair of damage to composites in aircraft structures are shown in Table 3-4. Bolted repairs are relatively straightforward and use many of the skills and tools used to repair metal structures. Hot-bonded repairs require more specialized expertise. Hot-bonded epoxy adhesives are generally used for bonding, and the structure to be repaired should be relatively dry before the patch is applied. Dryout for sandwich structure takes 24-48 hours, whereas laminate structure requires relatively shorter periods of controlled drying. Thus a major need for this kind of repair is a bonding material that cures rapidly at room temperature and can be used without drying the aircraft. Also needed are better NDE methods for field use and ways to repair filament-wound structures.

Emerging thermoplastic resin composites someday may be readily used to repair thermosets. Thermoplastic repair material should be storable for long periods at ambient temperature (up to 120 ° F) and capable of rapid processing with focused energy. Innovative repair procedures are more feasible if battle damage repair considerations are introduced at the design stage. A universal repair material that is easily processed is possible.

STATE OF THE ART

- FIELD-LEVEL REPAIRS (AFB, NAS & CARRIER)*
  - HOT-BONDED ADVANCED COMPOSITE THERMOSET MATERIALS
    4-IN.-DIAMETER DAMAGE TO 0.16-IN. THICK LAMINATES
  - BOLTED 0.16-IN.-THICK ALUMINUM & TITANIUM PLATES
    4-IN.-DIAMETER DAMAGE TO 0.4-IN. THICK LAMINATES

- DEPOT-LEVEL REPAIRS (ALC & NARF)**
  - HOT-BONDED ADVANCED COMPOSITE THERMOSET MATERIALS
    4- TO 8-IN.-DIAMETER DAMAGE TYPICAL OF F-18 STRUCTURE
  - BOLTED ALUMINUM & TITANIUM PLATES
    4- TO 8-IN.-DIAMETER DAMAGE TYPICAL OF AV-8B STRUCTURE
  - HOT-BONDED & BOLTED REPAIRS PER TO 1-1-690, GENERAL ADVANCED COMPOSITE REPAIR MANUAL, FOR F-15, F-16 & B1

* Air Force Base, Naval Air Station, aircraft carrier

** Air Logistics Center, Naval Air Rework Center

TABLE 3-4 REPAIR TECHNOLOGY FOR CURRENT ADVANCED COMPOSITE AIRCRAFT STRUCTURES

Source: Mahon, J., Grumman Aerospace Corporation

Several thermoplastic resins are of interest as repair materials for thermosets. Processing methods being evaluated include use of graphite reinforcement for resistance heating, a portable induction heating unit developed at NASA-Langley, ultrasonics, radiation curing, and off-site hot-forming methods. It should be noted that titanium is currently the only repair material suitable for graphite BMI components. A high temperature adhesive will be needed to repair future structures of this composite.

A new concept in repair that should be studied is automated battle damage assessment using a computer-based compilation of repair information. The computer would be interrogated in terms of specified details of the damage and would respond by identifying acceptable materials and procedures for repair. Such a system would best be based on a set of relatively simple materials and procedures.

METAL MATRIX COMPOSITES

Metal matrix composites are at a much earlier stage of development than organic matrix composites. Applications of these materials, as noted at the outset, are relatively few. Key matrices and reinforcements are shown in Table 3-5.

Interest in metal matrix composites stems from a mix of potential characteristics: superior high temperature properties; low coefficients of thermal expansion, contributing to dimensional stability; good survivability; and tailorable physical and mechanical properties. Silicon carbide/aluminum composites using continuous fiber have three times the strength and stiffness of unreinforced aluminum alloy; mechanical properties remain high at 500-600 ° F. SiC/aluminum has useful strength even at 800-900 ° F. Titanium matrix composites have good properties at 1000 °F or higher.

The processes used to make metal matrix composites are more complex than for organic matrix materials. High cost has been a major barrier to the use of metal matrix composites, and high material prices combined with labor-intensive fabrication methods have been a major contributor to cost. All the processes used to make parts involve high temperature. They have included hot pressing, casting, pressure casting, HIPing, extrusion, pultrusion, roll bonding, welding, and forging. All these processes can be adapted to net-shape fabrication.

Reinforcing fiber can be woven into preforms before investment casting with aluminum, and plasma spray preforms can be made for hot molding. Titanium matrix shafts can be made by rolling SiC fabric between foils and HIPing to the desired dimensions. SiC/titanium parts may be processed by superplastic forming and diffusion bonding. Despite the progress to date, aerospace uses of aluminum and titanium matrix composites in volume probably must await an expanded database and further improvement of manufacturing technology.

In addition to high manufacturing costs, applications of metal matrix composites have been limited by the high cost of reinforcements and a need for better high temperature reinforcements. Various reaction barrier coatings for fibers have been developed to prevent fiber/matrix interactions that occur at the high processing temperatures. Further, many of the key suppliers of materials are small companies with limited resources and need increased development funding.

Matrices	Reinforcements
• Aluminum	• Continuous fibers Boron (coated & uncoated) Silicon carbide Alumina Graphite
• Magnesium	• Wires Tungsten
• Titanium	• Discontinuous fibers Alumina Alumina-silica Graphite (chopped)
• Copper	• Whiskers Silicon carbide
• Superalloys	• Particles Silicon carbide Boron carbide Alumina

TABLE 3-5 METAL MATRIX COMPOSITES
KEY MATRICES AND REINFORCEMENTS

Source: Zweben, C. H., General Electric Company

Process Development

Development of reliable, affordable net shape fabrication processes for metal matrix composites warrants continued funding. Such development would include studies of fiber coating matrix interactions and work on process-modeling techniques. New high temperature reinforcements are needed, as noted earlier, as well as improved barrier coatings to prevent fiber matrix interactions. Also needed are alternate sources of materials supply.

Process development should be focused on methods for fabricating net shape components with high payoffs. For composites with continuous fiber reinforcement, squeeze casting is particularly attractive. NDE is even more critical and complex than it is for organic matrix composites because of the possibility of degradation of fibers owing to fiber matrix interaction at process temperatures. New NDE methods are needed to determine fiber degradation.

Applications Development

Needs in development of applications for metal matrix composites include better design methods. It is also time to select secondary structural components for near-term development and production. A longer term goal is development of the technology for using these materials in heavily loaded structures. A planned test article is the ATF vertical stabilator shown in Figure 3-9, which will use aluminum reinforced with silicon carbide. Four test stabilators are planned. Avco Corporation is to supply continuous SiC-reinforced aluminum for the skins of two of them and for the substructures of all four; Arco Chemical Company will supply whisker SiC aluminum for the skins of two stabilitors. The program is being conducted by Lockheed for the Air Force Flight Dynamics Laboratory. Static and fatigue tests are scheduled for 1988.

Commercial applications of metal matrix composites also should be studied. One example involves Art Metal Company in Japan, which is making fiber-reinforced aluminum pistons for diesel engines for Toyota. The process is squeeze casting, and the production rate is estimated at 300,000 per year. An application that has received too little attention is packaging for electronic and microwave devices. Their unique combination of low thermal expansion and high thermal conductivity makes metal matrix composites well suited to packaging (as well as to engine and spacecraft applications). A small technical effort should be established to follow commercial developments in these materials in the U.S. and abroad. Such developments could spin off into the military aerospace field.

CERAMIC MATRIX COMPOSITES

Ceramic matrix composites, excepting carbon-carbon, are at an even earlier stage of development than metal matrix materials. Key matrices and reinforcements are shown in Table 3-6. Funding for ceramic matrix composites has been very limited, again excepting carbon-carbon. This material is being developed for jet engine parts and, as noted earlier, has production uses that include aircraft brakes and rocket nozzles.

Note: Material is to be aluminum reinforced with silicon carbide continuous fibers or whiskers

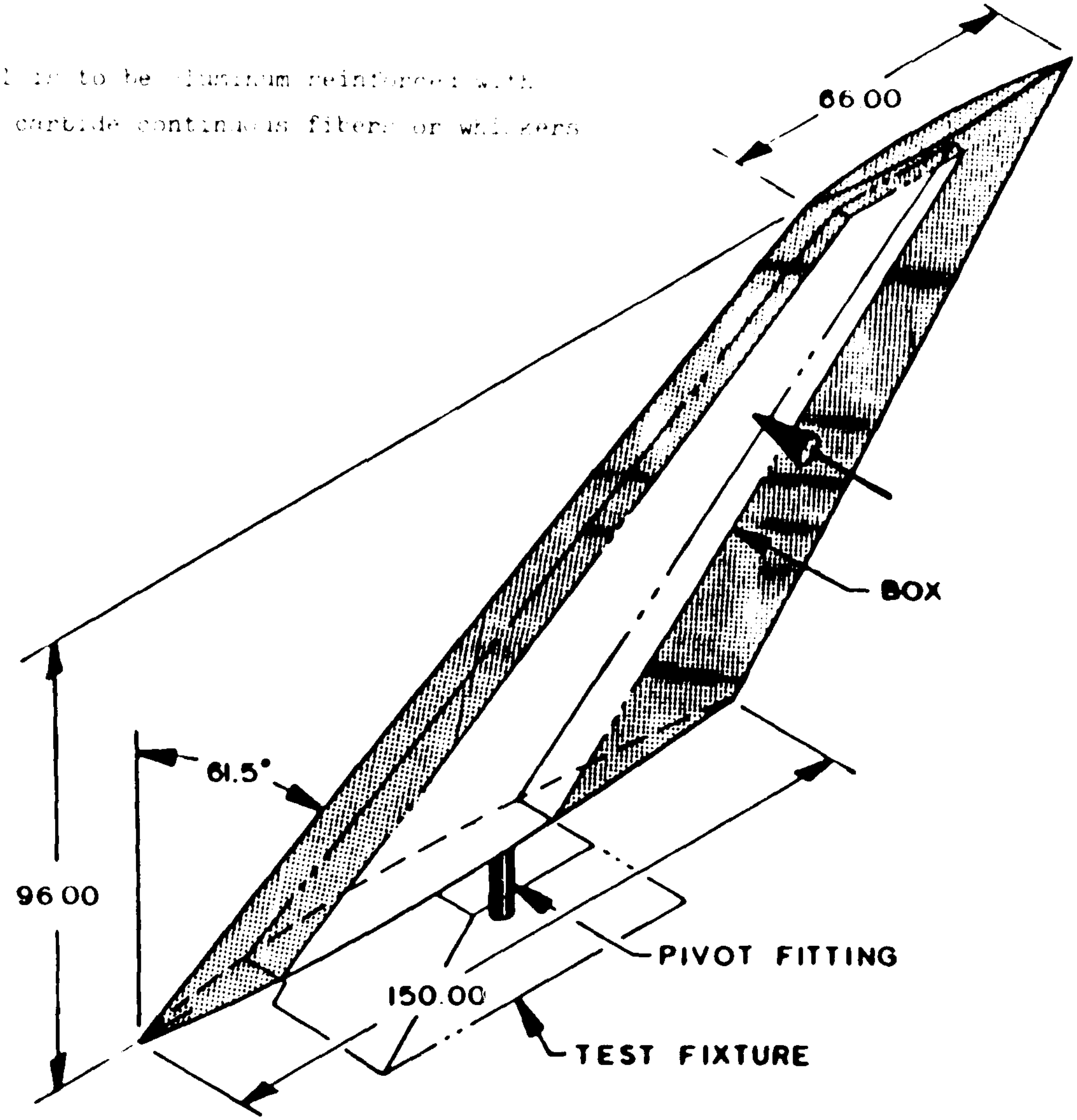


FIGURE 3-9 FULL-SCALE TEST ARTICLE - ATF VERTICAL STABILATOR

Source: Hoffman, P. R., Avco Corporation

AD-A176 508 NET SHAPE TECHNOLOGY IN AEROSPACE STRUCTURES VOLUME 1 2/2
(U) NATIONAL RESEARCH COUNCIL WASHINGTON DC COMMITTEE
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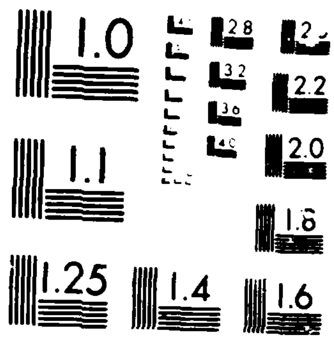

1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

Matrices	Reinforcements
• Carbon	• Continuous fibers Glass Graphite Boron Silicon carbide Silicon nitride Alumina
• Glass	
• Glass ceramic	
• Silicon carbide	
• Silicon nitride	• Whiskers Silicon carbide
• Alumina	

TABLE 3-6 CERAMIC MATRIX COMPOSITES
KEY MATRICES AND REINFORCEMENTS

Source: Prewo, K. M., United Technologies Research Center

The properties that make metal matrix composites attractive are also found in ceramic matrix materials, which have even better high temperature potential and reduced radar detectability. The characteristically low toughness of high performance ceramics can be improved by use of reinforcing particles or fibers. Ceramic matrix composites incorporating very strong ceramic fibers have been shown to be similar to graphite/epoxy composites in structural toughness and reliability. The maximum operating temperatures of these materials may exceed 2400° F, compared to only about 600 ° F for organic matrix composites. Processes used to make ceramic matrix composites include chemical vapor infiltration (CVI), sintering, hot pressing, HIPing, melt infiltration, sol-gel, precursor infiltration/pyrolysis, and slurry mixing (for portland cement).

Only two glass matrix composite technologies have reached the component testing stage. One involves application of the matrix to preformed, net shape reinforcement by CVI. In the other, composites with glass and glass ceramic matrices are fabricated much like organic matrix composites: a tape of reinforcement impregnated with a glass frit slurry is laid up and pressed to net shape at a temperature that renders the glass sufficiently fluid to permeate the reinforcement thoroughly. These composites can be made by other processes, such as matrix injection and use of chopped-fiber molding compounds.

A French firm is supplying experimental gas turbine parts, including integrally bladed rotors, made by the CVI process; the matrix is silicon carbide and the fiber is silicon carbide or carbon. The CVI process has been used in this country by Amercom Inc. to make large parts such as tubes 8 ft. long and 8 in. in diameter. United Technologies Research Center (UTRC) and Corning Glass Works have made gas turbine test parts with glass and glass ceramic matrices. UTRC also has made parts for testing in a diesel engine, as gun barrel liners, as shaft seals, and as components for space-based lasers. The company sees the possibility that gas turbine parts will be made in large quantity from glass matrix composites in this country within the next five years.

Development of improved ceramic fibers is being funded by the Air Force Materials Laboratory (AFML) and the Defense Advanced Research Projects Agency (DARPA). The program has produced SiC fiber with properties equivalent to those of Nicalon (a Japanese fiber of the SiC class). Greater uniformity in the strength of SiC filaments and tows is also being achieved. Current work is aimed at greater strength and thermal stability, development of a silicon nitride fiber, and improved coatings to reduce fiber/matrix interactions. The AFML/DARPA program is still in the research stage.

Work on carbon-carbon composites for jet engines has several goals: lower weight, better performance, greater durability, and reduced dependence on strategic materials. Near-term applications include nozzle/augmentor flaps, cases, seals, and liners. Longer term uses may include combustor/turbine blades, disks, and vanes. A sound engineering base is evolving, and component testing is under way.

Process Development

Development of reliable net shape processes for ceramic matrix composites, as with the metal matrix materials, calls for a balanced approach. The major need currently is materials and process development. Both the materials and processes available are limited and far from mature. High temperature reinforcements and fiber matrix reaction barrier coatings are needed. Among several areas of basic science that need work is the micromechanics of toughening and strengthening brittle matrices. Better NDE methods are required, again because of the possibility of fiber degradation by reaction with the matrix.

Applications Development

Development of applications for ceramic matrix materials should be focused initially on secondary structures such as high temperature radomes. Success in these areas can lead to more critical uses as the technology matures. Also, the materials have great potential in electronic and microwave packaging and other uses because they can be tailored to obtain combinations of properties not possible with monolithic materials. A novel, nonstructural use of advanced ceramic matrix composites has reached a commercial stage at Arco Chemical Company, which is supplying alumina reinforced with silicon carbide whiskers for volume production of cutting tools.

RECOMMENDATIONS

To achieve the required improvement in manufacture of high quality, affordable net shape composite aerospace parts, we recommend that action be taken on the following needs:

Materials

1. Improved tools and methods to sharply upgrade the physical and chemical consistency and quality of thermoset resin prepreg tape and fabric used to make organic matrix composites consistent with the variability in geometry involved.

2. A shift in emphasis from R & D on many competing composite materials to establishment of standardized, fully qualified classes of materials.

3. Establishment of a National Center, with DoD coordination, to qualify individual materials under a set of uniform standards for different classes of materials.

4. A concerted effort to establish a Military Handbook on composites to provide standards for characterization of materials, acceptable levels of flaws and defects in finished parts, and other parameters essential to orderly development, manufacture, and quality assurance of composite aerospace parts.

5. Increased R & D funding of metal, ceramic, and carbon matrix composites to support work specified in R & D road maps proposed for these materials.

6. Establishment of small technical efforts to monitor commercial activities in organic, metal, and ceramic matrix composites in the U.S. and abroad for developments that could be applied to specific DoD needs and problems with aerospace vehicles.

Manufacturing

7. Coordination and careful monitoring of design-manufacturing integration in organic matrix composites to insure that surge capability is not seriously hindered by development of unique engineering approaches and facilities by individual manufacturers. Provision of a "bottom-up" and "top-down" approach to computer integration of manufacturing and processing functions.

8. program to identify issues that must be resolved to take full advantage of automated manufacture of composites, including confidence in unmanned operation, start-up and support costs, quality control, design for automation, and need for reliable, affordable, net shape fabrication processes.

9. Continued evaluation and monitoring of the development of pultrusion technology, which promises affordable manufacture of straight, constant crosssection parts, using both thermoset and thermoplastic resin composites.

10. Continued funding of technology development in injection molding, where special resins and techniques must be used.

11. Special inexpensive fasteners for organic matrix composites that are tolerant of variations in the thickness of composite laminates.

12. Costing methods that permit costs of composite parts to be accurately predicted, taking into account the effects of a fully integrated, automated manufacturing facility.

13. Development of uses for aerospace composites that do not require their ultimate capabilities (such as in secondary aircraft structures or consumer products) to build production volume that will provide experience with the manufacture and behavior of materials.

14. Funding for the development of reliable, affordable, net shape fabrication processes for metal and ceramic matrix composite parts.

15. Air Force sponsorship of university positions in composite manufacturing at leading schools across the country.

Nondestructive Evaluation

16. Techniques and sensors required for continuous, real-time, automated processing and NDE of composite materials at all stages of manufacture, and automation of NDE procedures when warranted by the volume of materials or numbers of parts to be produced.

17. Adequate methods for NDE of the strength of organic matrix composite bonds to reduce reliance on metallic fasteners and the associated drilling for assembling composite structures.

Repair

18. Early development of battle damage repair procedures for both thermoset and thermoplastic composite aerospace parts using thermoplastic materials, with emphasis on portable energy sources. Repair information should be provided in formats compatible with automated battle damage assessment aids. A bonding material, for repairing battle damage to thermoset composite structures, that cures quickly at room temperature and can be used without drying the structures.

Applications

19. Air Force contracts that foster development of composites technology by teams of prime contractors, subcontractors, and material and equipment suppliers, rather than for major demonstration projects, which often have failed to advance the state of the art or transfer the technology throughout industry.

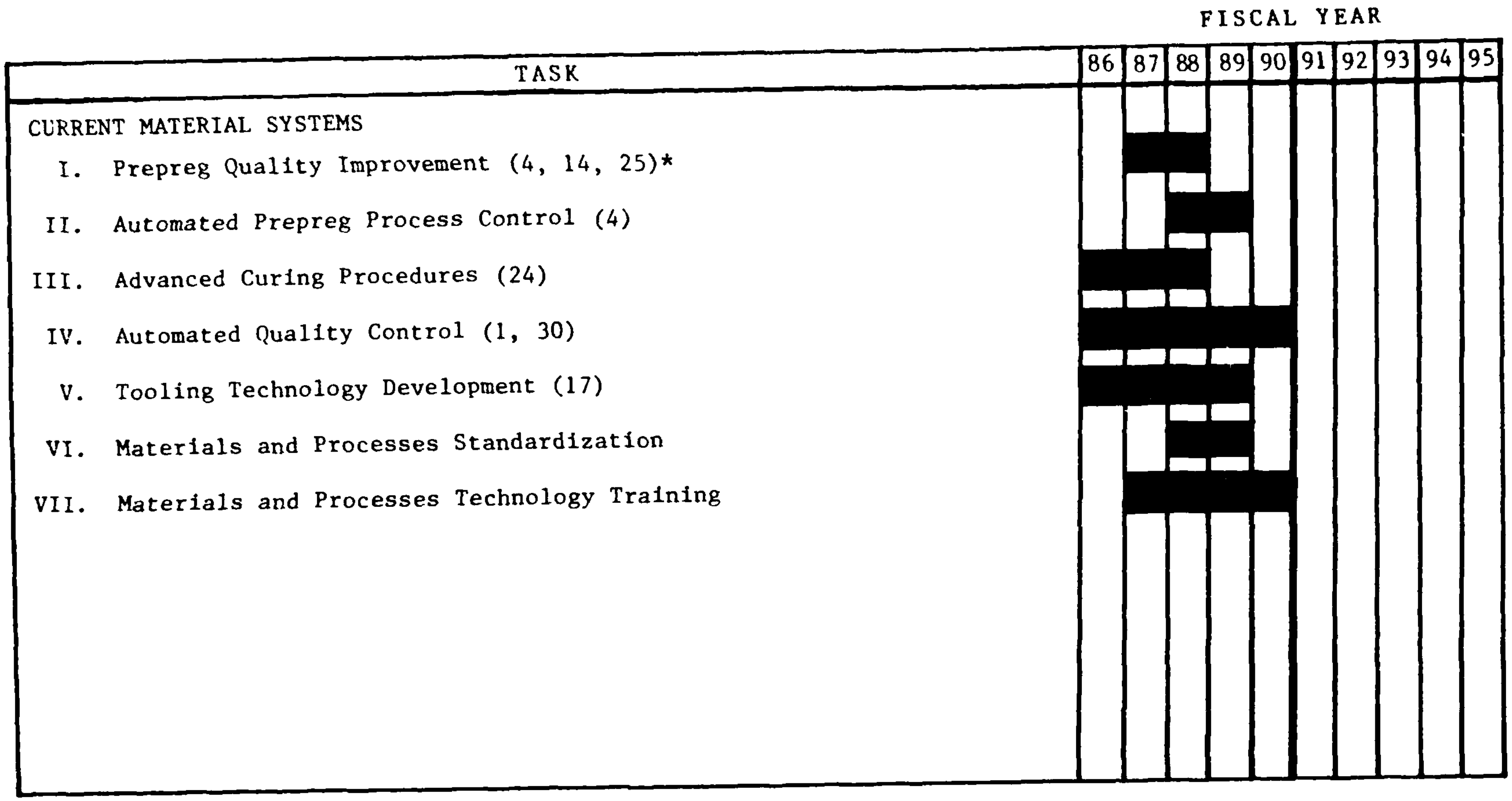
20. A mechanism for rapidly funneling relatively small amounts of Air Force discretionary funds - in the range of $500,000-$800,000 - to companies to support development aimed at critical technological needs.

R&D ROAD MAPS

Working from the needs identified above, the committee developed nine road maps for R & D in composite materials development and manufacturing technology. They are designed to assure prompt and orderly achievement of the full potential of net shape manufacture of composite parts for aerospace structures. These road maps, (see pp. 95-103), depict a coordinated R & D program. They show the tasks to be pursued and the years of effort likely to be required. The different starting times shown by the bars and gaps in the bars indicate that work on various tasks must await the results of related efforts before it can begin or continue.

Following the road maps is a numbered list of workshop speakers and the titles of their papers (which comprise Volume IV of this report). After each task on the road maps, these papers are cited where appropriate in parentheses.

ROAD MAP 3-1 THERMOSET ORGANIC MATRIX COMPOSITES I



GOALS

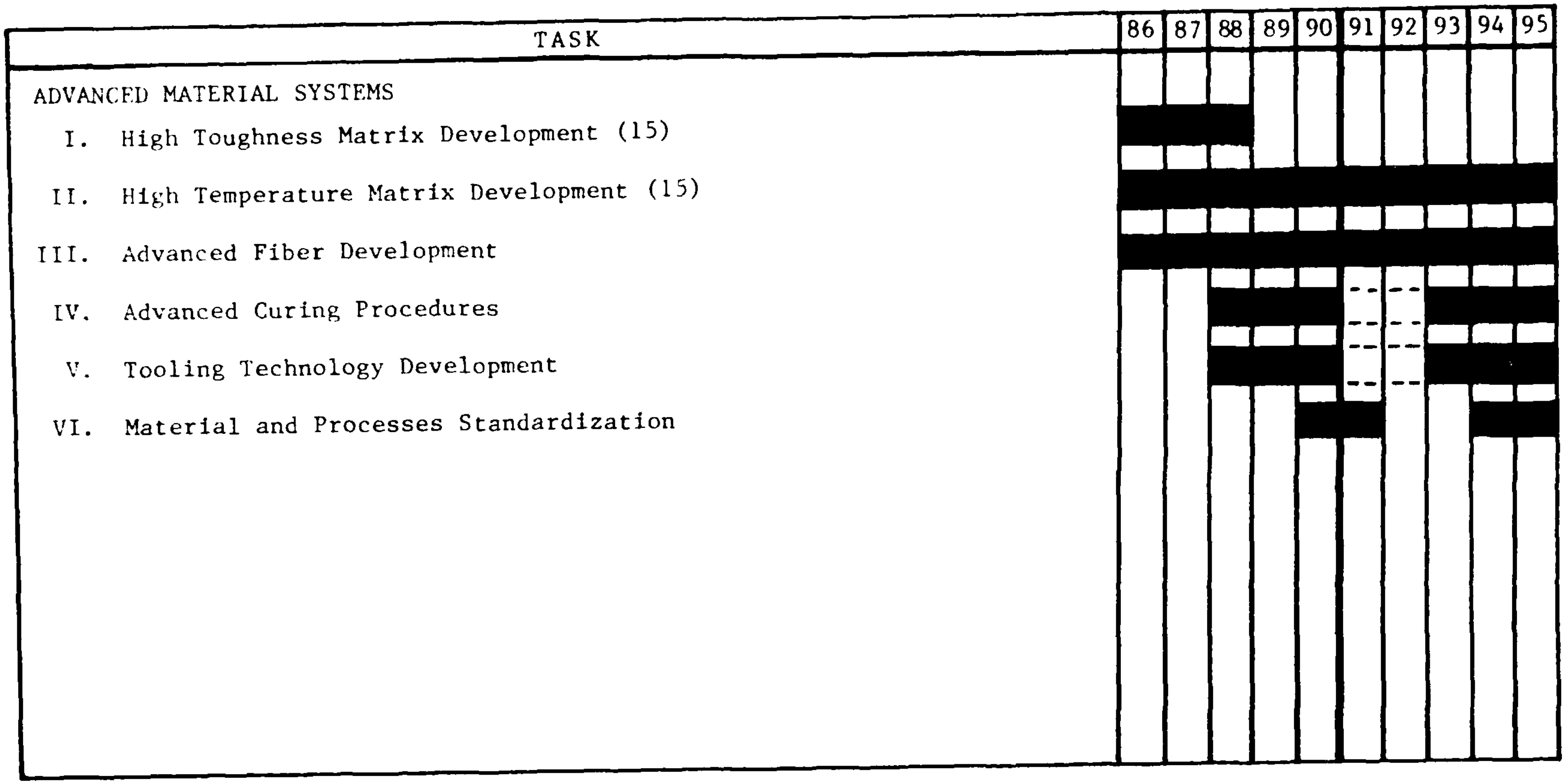
- Uniform specifications
- Quality improvement
- Uniform specifications and standards - materials and processes

PAYOFFS

- Significant cost reduction with improved quality

*Numbers indicate references listed on pages 104-5. These references are in Volume IV.

ROAD MAP 3-2 THERMOSET ORGANIC MATRIX COMPOSITES II



GOALS

- 10x improvement in toughness
- Epoxy/BMI: 350°F capability by 1988
- PI, Other: 700°F capability by 1990
- Other: 900°F capability by 1995

PAYOFFS

- Material applicable to aerospace system needs for the late 1990s

ROAD MAP 3-3 THERMOSET ORGANIC MATRIX COMPOSITES III

TASK	FISCAL YEAR 86	87	88	89	90	91	92	93	94	95
MANUFACTURING										
I. Automated Part Fabrication (20)										
(a) Automated laminating (21)	■	■	■							
(b) Filament winding (19)		■	■	■						
(c) Pultrusions (22)		■	■							
(d) Innovative concepts		■	■	■	■	■	■	■		
(e) Quality assurance (1, 29, 30)		■	■	■	■	■	■	■		
II. Automated Assembly (26, 27, 28)										
(a) Mechanical joints	■	■	■							
(b) Bonded joints	■	■	■	■						
(c) Quality assurance (1, 29, 30)		■	■	■	■	■				
III. Design-Manufacturing Integration (8, 10, 18)										
(a) Specifications/Standards			■	■			■	■		
(b) Effects of defects		■	■	■	■	■	■	■		
(c) Quality assurance (1, 29, 30)		■	■	■	■	■	■	■		
(d) CAD/CAM/CAE		■	■	■	■	■	■	■		
(e) Data base		■	■	■	■	■	■	■		
IV. Repair (31, 32)										
(a) Manufacturing damage		■	■	■	■	■	■	■		
(b) Service damage		■	■	■	■	■	■	■		

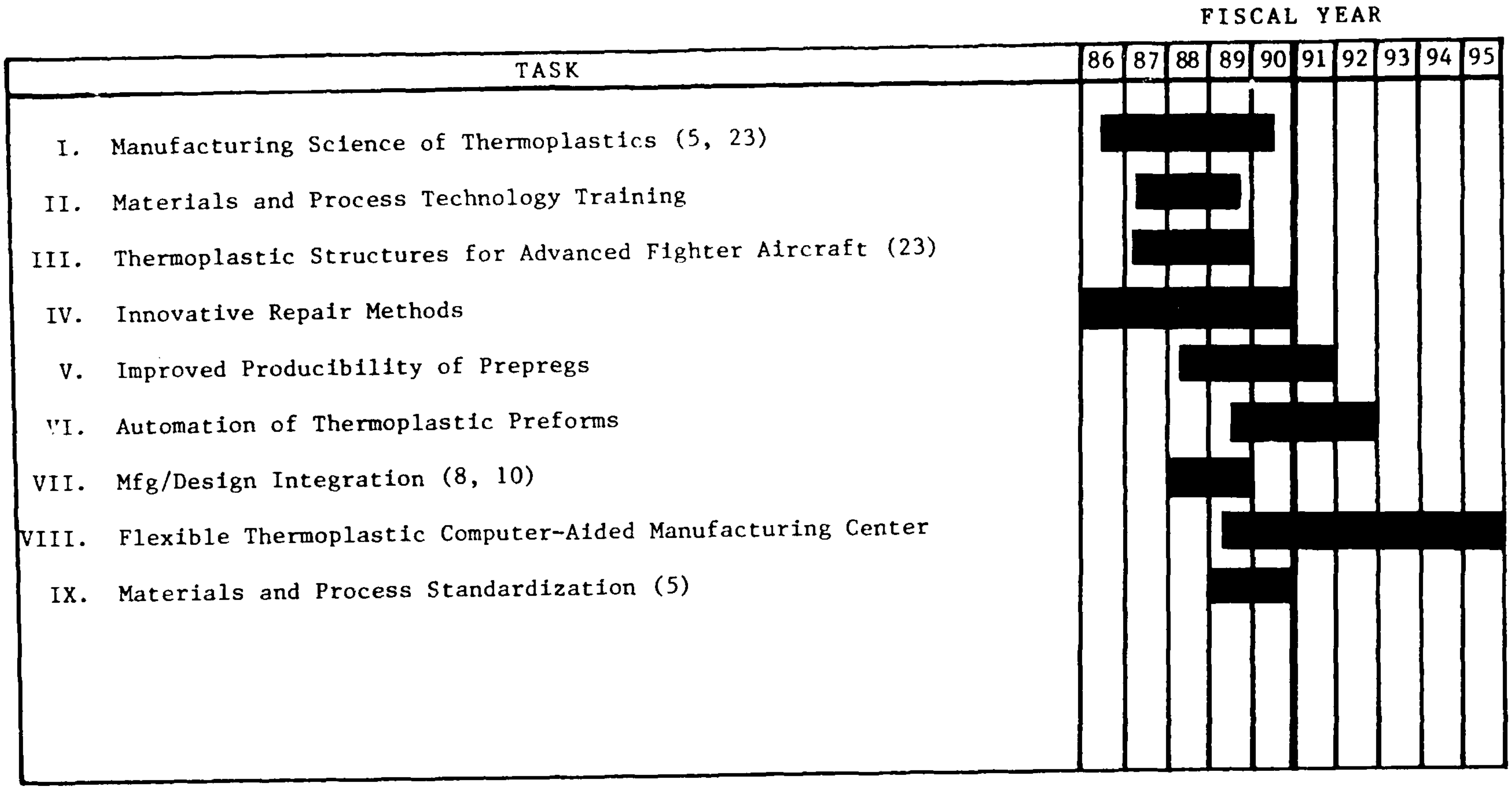
GOALS

- 50% reduction in manufacturing labor
- Improved quality

PAYOFFS

- Significant cost reductions

ROAD MAP 3-4 THERMOPLASTIC AIRCRAFT STRUCTURES



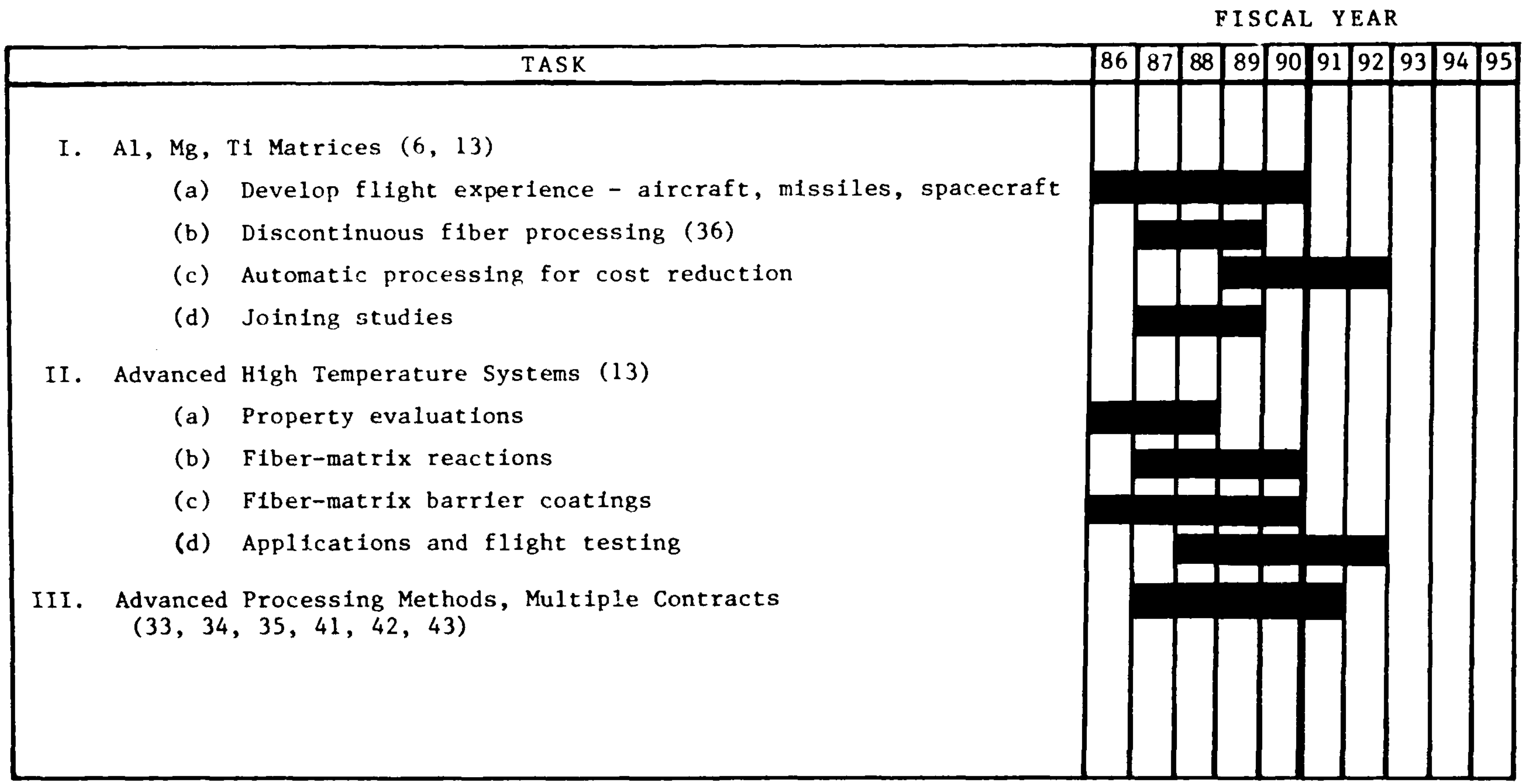
GOALS

- Validated manufacturing technology for cost-competitive thermoplastic composites

PAYOFFS

- Improved performance (toughness)
- Lower life cycle costs
- Reduction of scrap parts
- Low-cost field repairs
- Improved aircraft reliability
- Standard material storage

ROAD MAP 3-5 METAL MATRIX COMPOSITES



<u>GOALS</u>

- Reduced processing cost
- Reliable fabrication processes
- Multiple sources of material supply

<u>PAYOFFS</u>

- Ductile, crack-resistant matrix
- Higher use temperature
- Low outgassing for space structures

ROAD MAP 3-6 CARBON-CARBON COMPOSITES

TASK	86	87	88	89	90	91	92	93	94	95
I. Emphasis on Processing 2D and 3D Materials for Structural Use	■	■	■	■						
II. Automated Process Control and NDE for Carbon-Carbon Materials (7)		■	■	■	■	■				
III. Improved Oxidation-Resistant, Thermal-Cycling Resistant Coatings and Fiber-Matrix Reaction Barriers (40)	■	■	■	■						
IV. Studies of Cost-Effective Processing Methods (7, 40)			■	■	■	■	■			
V. Joining of Carbon-Carbon to Dissimilar and Similar Materials		■	■	■	■					

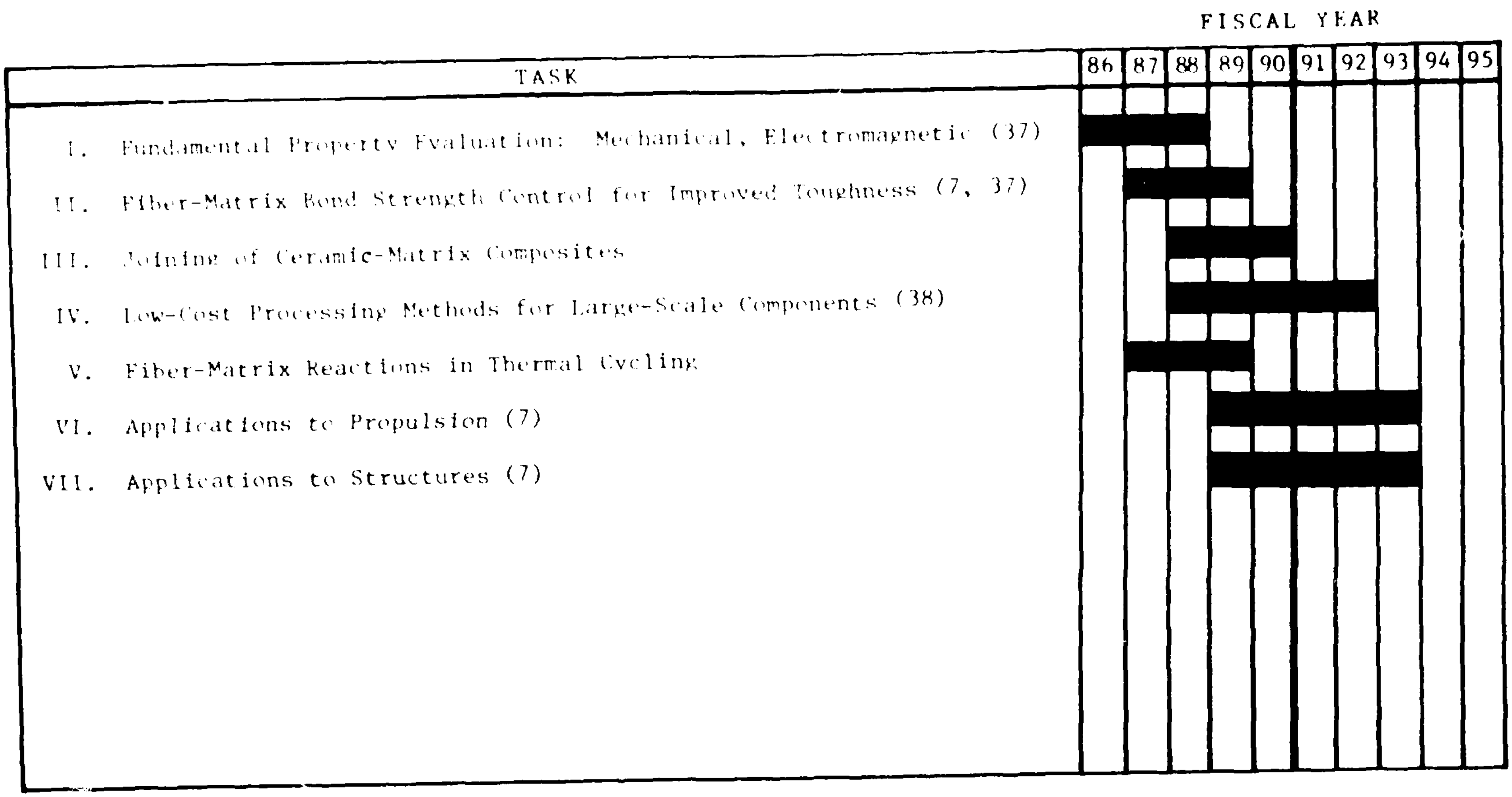
GOALS

- High-rate, lower-cost processing
- Understanding process variables
- Improved NDE
- Net shape woven, braided 2D, 3D structural materials

PAYOFFS

- Extremely high-temperature use
- Excellent specific strength and stiffness

ROAD MAP 3-7 CERAMIC MATRIX COMPOSITES



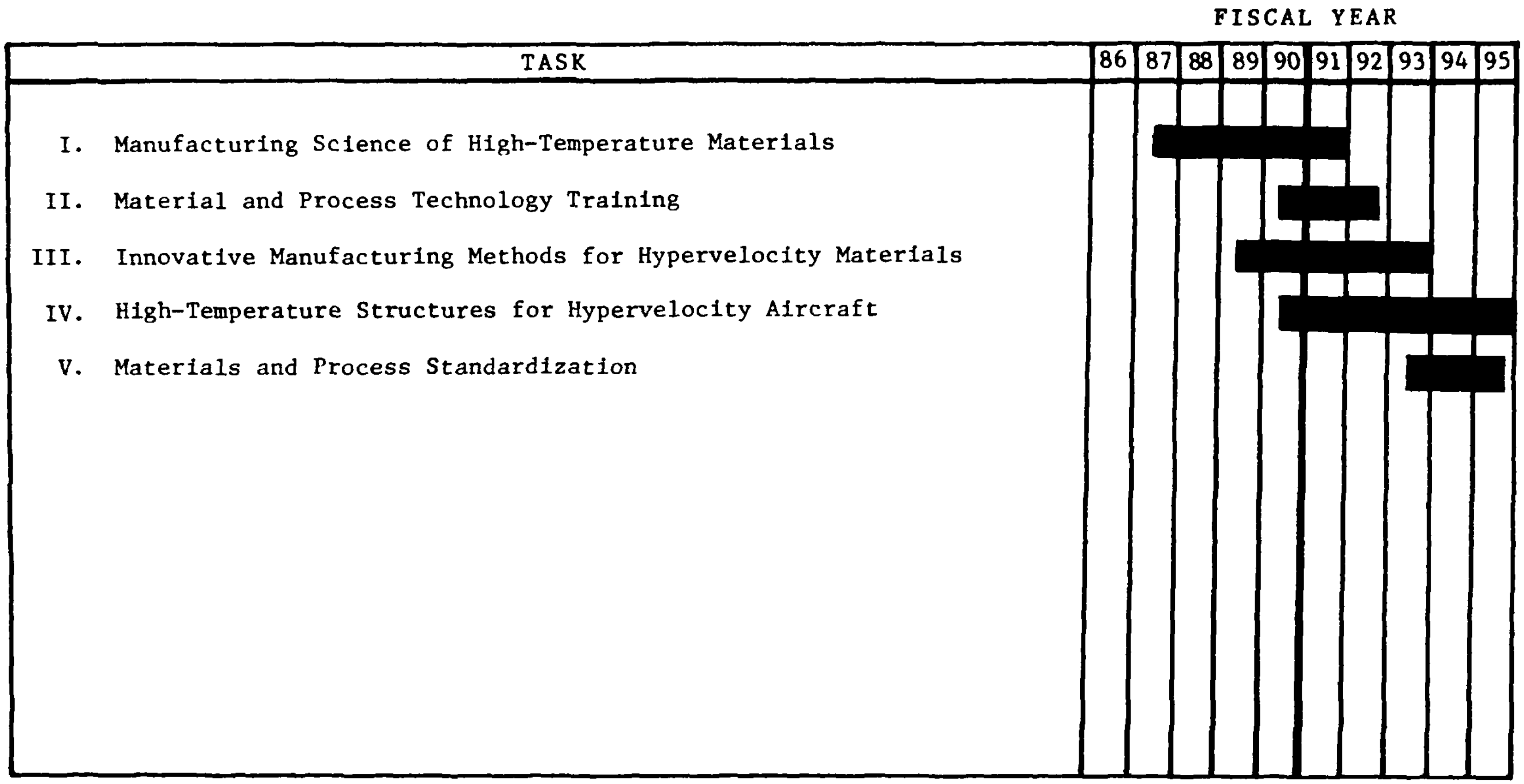
GOALS

- Understanding bond strength-toughness interaction
- Improve uniformity of properties
- Develop rapid, low-cost processing methods
- Understand processing variables

PAYOFFS

- Oxidation resistance at very high temperature
- Promising electromagnetic properties
- Excellent specific strength and stiffness at high temperature
- Machine tool life

ROAD MAP 3-8 HIGH-TEMPERATURE (>1500°F) COMPOSITES MANUFACTURING TECHNOLOGY



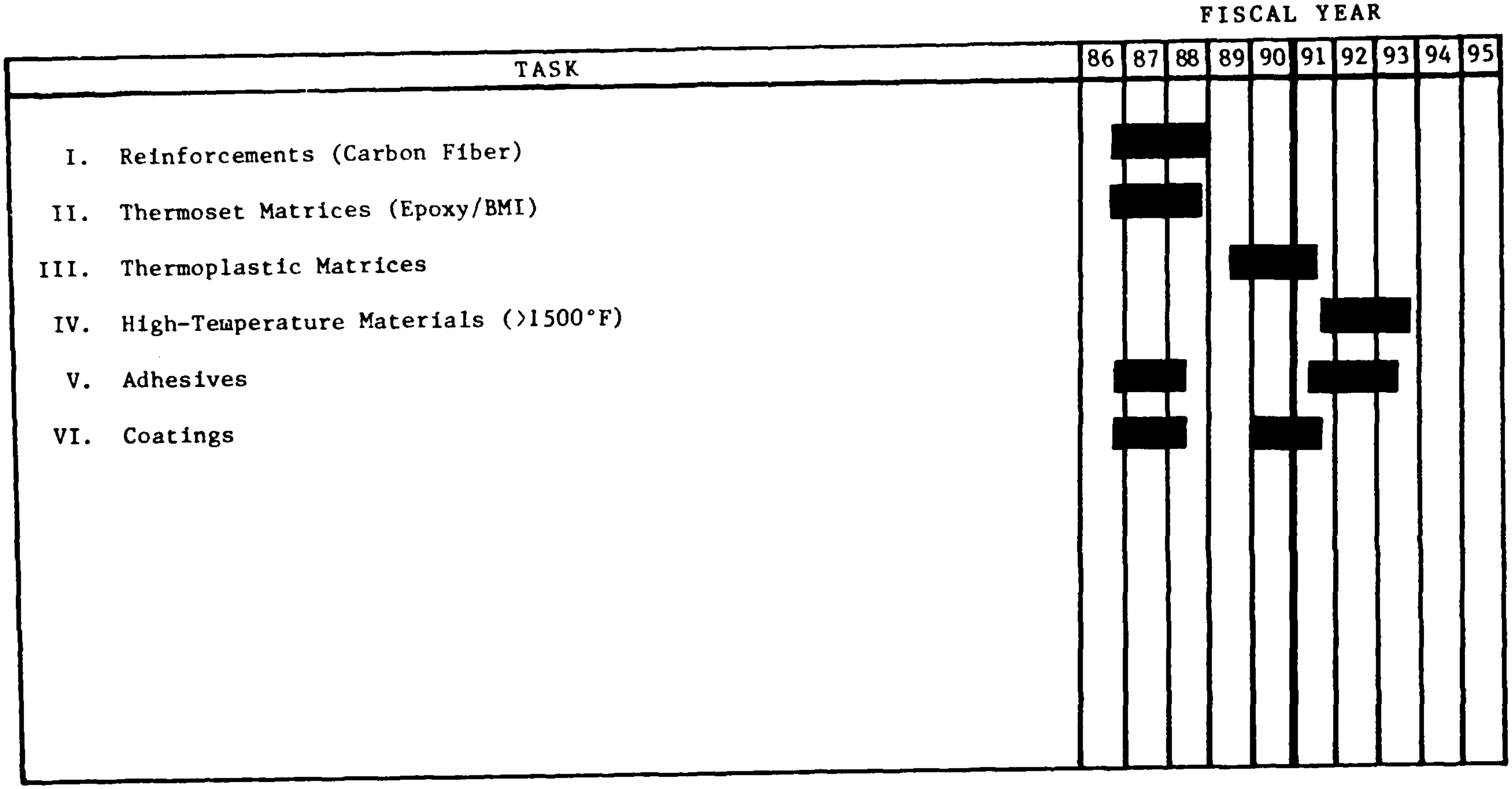
GOALS

- Establishment of a manufacturing baseline for hypervelocity applications and develop improved manufacturing technology for competitive life-cycle costs

PAYOFFS

- Competitive manufacturing capabilities
- Establish leading edge manufacturing technologies for high-temperature applications
- Increase size capability

ROAD MAP 3-9 STANDARDIZATION OF COMPOSITES MATERIALS



<u>GOALS</u>

- Reduce materials qualification costs
- Enhance competition
- Enhance industry data base

<u>PAYOFFS</u>

- Lower aircraft costs
- Expanded materials use
- Reduced risk

WORKSHOP 3 SPEAKERS[a]

1. Persh, Jerome. Keynote Address.

2. Pirrung, Paul F. Air Force Program Overview.

3. Dilley, David. "Blueprint for Tomorrow," An Air Force/Industry Assessment of the Industrial Base.

4. Forest, David. Thermoset Polymer Materials.

5. Gibbs, Hugh H. The Whys and Wherefores of Thermoplastics in Advanced Composites.

6. Hoffman, Paul R. Silicon Carbide Fiber Metal Matrix Composite Materials.

7. Schmid, T. E. Carbon-Carbon and Ceramic Matrix Composites.

8. Crossman, F. W. Design-Manufacturing Integration.

9. Ashton, Larry. A New Idea is an Alternative: A Cost-Effective New Idea is an Innovation.

10. Von der Esch, Albert H. Manufacturing System Integration.

11. Steelman, Thomas E. Comments on Reinforcing Materials.

12. Busch, John. Economic Modeling of Composites Manufacturing.

13. Zweben, Carl. Metal and Ceramic Matrix Composites.

14. McKague, Lee. A Call for New Action in Thermosetting Resin Technology.

15. DiSalvo, Gail. Organic Matrix Resins: State-of-the-Art and Technology Needed to Reduce Costs and Increase Usage.

16. Hood, Paul. Material Forms and Near-Net Shaping of Engineered Metallic Composites.

17. Kollmansberger, R., and P. Oliva. Innovative Tooling Development for Aerospace Composite Materials: A Status Report.

18. Roquemore, John R. Transport Aircraft Design/Tooling Integration.

19. Wilson, Brian A. Filament Winding Technology.

20. Taylor, A. T. Tape Laying Technology Automated.

21. Smith, D. L. Automated Ply Laminating System.

22. Jones, Brian H. Pultrusion.

[a] The material submitted for publication by these speakers appears in Volume IV of this report.

23. Stout, R. J. Thermoplastic Composite Technology Development.

24. Poveromo, Leonard. Future Composite Manufacturing Technology: Advanced Curing Concepts.

25. Borstell, Hans J. Reducing Costs of Shimming-Prefit.

26. Hall, Terence F. W. Automated Assembly.

27. Marx, Warren. Composite Assembly.

28. Spinks, Donald G. Composite Assembly Proposals.

29. Harris, G. E. Future Quality Assurance Technology.

30. Chance, Richard F. Comments on Quality Control.

31. Mahon, Jack. Thermoplastic Repair Procedures for Future Advanced Composite Structures.

32. Carrier, W. L. Repair of Composite Structures - An Overview

33. Cornie, James A. Semi-Solid Slurry Processing of Metal Matrix Composites.

34. Chellman, D. J., and W. F. Bates. Metal Matrix Composite Manufacturing Technology.

35. Gurganus, Thomas B. Fabrication and Forming of Metal Matrix Composites.

36. Ghosh, A. K. Deformation Processing of Discontinuously Reinforced Metal Matrix Composites.

37. Hauth, W. E. Polymer-Derived Ceramic Fibers and Ceramic Matrix Composites: A Review of the DARPA Initiative.

38. Prewo, Karl M. Hot Pressing Fabrication of Glass Matrix Composites.

Prewo, Karl M. Ceramic and Carbon Fiber Reinforced Glasses.

39. Johnson, David W. Manufacturing for Applications of Carbon-Carbon to Leading Edge and Nose Cap of the Space Shuttle.

40. Schmid, T. E. Application of Carbon-Carbon for Engines.

41. Dolowy, J. F. Metal Matrix Composites: Man-Tech Areas of Need/Net Shape Processing.

42. Goddard, David M. Casting of Continuously Reinforced Metal Matrix Composites.

43. Foltz, Thomas F. Emerging Composite Manufacturing Technology.

44. Palmer, Raymond J. Tooling and Forming Processes.

45. Hettinger, William. General Purpose Carbon Fiber.

APPENDIX A

Workshop 1 Presenters

Taylan Altan, Battelle Memorial Institute
Charlie C. Chen, Chen-Tech Industry Inc.
Robert P. Daykin, Ladish Company
Harold L. Gegel, AFWAL/MLLM, Wright Patterson AFB, OH
Tom E. Griffin, Aluminum Forge, Inc.
Greg Henderson, General Dynamics
James A. Hicker, Boeing Company
Sol Love, Private Consultant
Lloyd Lynch, Bell Helicopter Company
John McKeogh, Wyman-Gordon
Joe Melill, Northrop Corporation
James W. Nelson, Aluminum Company of America
Michael J. Reed, ASD/PMD, Wright-Patterson AFB, OH
William T. Richards, McDonnell Aircraft Corporation
Tibor Serfozo, Lockheed-California Company
Aly Shabaik, U. of California, Los Angeles
Mike Spinelli, Aluminum Precision Products, Inc.
Larry Wagner, General Aluminum Forge, Inc.
Bryant H. Walker, Pratt & Whitney Company
B. J. Webster, Martin-Marietta Aluminum Co.
John F. Workman, Lockheed-California Company
Bruce Zelus, North American Aircraft Operation, Rockwell International

Workshop 1 Attendees

Don H. Baker, Jr., Albany Titanium Inc.
Gregory B. Barthold, Aluminum Company of America
Thomas Bauman, Northrop Corporation
John Bimshas, Charles Stark Draper Laboratory
Robert Brockett, Lockheed-California Company
Weldon E. Burgess, Boeing Company
David Ciscel, ASD/B1BD, Wright-Patterson AFB, OH
Robert Darke, Aluminum Company of America
James Donovan, Weber Metals, Inc.
Bruce Ewing, Allison Gas Turbine, Division of General Motors
Peter C. George, Boeing Company
Charles Gure, Chen-Tech Industry Inc.
Khang Hoang-Vu, Shultz Steel Company
Frank H. Keckeissen, Lockheed Missiles & Space Company
Joseph R. Lane, National Materials Advisory Board, NRC
David Lopez, Weber Metals, Inc.
Charles C. Lowery, Lockheed Georgia Company
Tom Matulaitis, Wyman-Gordon
Alan K. Miller, Stanford University
George Mochnal, Sifco Industries
James J. Nevins, Charles Stark Draper Laboratory
Thomas Newell, Aluminum Precision Products, Inc.

George Petronio, Grumman Aerospace Company
Robert Pishko, Aluminum Company of America
Edward Raymond, Cameron Iron Works
Jim Shannon, Wyman-Gordon
Gordon Shultz, Schultz Steel Company
Stewart Smith, Cameron Iron Works
Olley W. Stellfox, Boeing Company
Gary Strong, North American Aircraft Operations, Rockwell International
Don Widner, Weber Metals, Inc.
Les Wilshire, Vought Corporation
L. E. Wirtz, Lockheed Missiles & Space Co.
Jack Yoblin, Private Consultant

APPENDIX B

Workshop 2 Presenters

Peter Bridenbaugh, Aluminum Company of America
Sherman D. Brown, U. of Illinois at Urbana-Champaign
Rointan F. Bunshah, U. of California at Los Angeles
Art Cox, Pratt & Whitney Aircraft Group
E. J. Dulis, Colt Industries
Amit Ghosh, Rockwell International Science Center
Ralph Hecht, Pratt & Whitney Aircraft Group
Russ Hill, Airco Temescal Corporation
Anthony M. Ledger, Optical Coating Laboratory, Inc.
Louis W. Lherbier, Cytemp Specialty Steel Division, Cyclops Corp.
John Mangels, Ford Research
Robert Mehrabian, U. of California, Santa Barbara
Donald Muzyka, Cabot Corporation
Steve Ping, Kaiser Aluminum and Chemical Corporation
Karl Prewo, United Technologies Corporation
David Richerson, Ceramatec
Angus Rockett, U. of Illinois at Urbana-Champaign
B. O. Seraphin, U. of Arizona
David Schuster, Science Application International Corporation
Robert A. Sprague, General Electric Company
Peter C. Smith, GTE Wesgo
Edward D. Weisert, Ontario Technical Corporation

Workshop 2 Attendees

Don H. Baker, Jr. Albany Titanium Inc.
John Bimshas, Charles Stark Draper Laboratory
Ken Bird, Albany Titanium Inc.
Lisa Blough, General Dynamics
William J. Boesch, Private Consultant
Michael Buckley, Rockwell International Science Center
Charles M. Byrne, Kaiser Aluminum and Chemical Corporation
Charlie C. Chen, Chen-Tech Industries Inc.
Andrew Crowson, U. S. Army Research Office
Michael DeCresente, United Technologies Research Center
L. Duane Dunlap, Aluminum Company of America
Bruce Ewing, Allison Gas Turbine
Frank Frechette, Research & Development Center, Sohio Engineered Materials Company
Dale Gieseking, Boeing Aerospace Company
Tom E. Griffin, Aluminum Forge, Inc.
Robert F. Gosinhfin, Boeing Military Airplane Company
Arthur Hayes, Ladish Company
John Huebner, McDonnell Aircraft Corporation
A. A. Hendrickson, Michigan Technological University
Edward S. Hodge, Air Research Casting Company
Maurice Howes, IIT Research Institute
Frank H. Keckeissen, Lockheed Missiles & Space Company

Philip Keeler, Aluminum Precision Products, Inc.
Joe Melill, Northrop Corporation
Thomas E. Miles, Chen-Tech Industries Inc.
Michael Mitchell, Rockwell International Science Center
Tapas Mukherji, Lockheed Advanced Aerospace Corporation
James L. Nevins, Charles Stark Draper Laboratory
Soo-Ik Oh, Battelle Columbus Laboratories
Henry G. Paris, Aluminum Company of America
Vimal K. Pujari, Norton Company
S. Victor Radcliffe, National Forge Company
Edward Raymond, Cameron Iron Works
Kay Rhyne, National Bureau of Standards
J. T. Ryder, Lockheed Advanced Aeronautics Corporation
Bernard Tittmann, Rockwell International Science Center
Robert Widmer, Industrial Materials Technology
N. A. Wilkinson, Cameron Iron Works
Les Wilshire, Vought Corporation
H. Thomas Yolken, National Bureau of Standards
Robert L. Zwart, Fairchild Republic

APPENDIX C

Workshop 3 Presenters

Larry J. Ashton, Fiber Technology Corporation
William F. Bates, Jr., Lockheed-Georgia Company
Hans J. Borstell, Grumman Aerospace Corporation
John Busch, Massachusetts Institute of Technology
William L. Carrier, McDonnell Douglas Corporation
Richard F. Chance, Grumman Aerospace Corporation
David J. Chellman, Lockheed-California Company
Frank Crossman, Lockheed Missiles and Space Company
David A. Dilley, Wright-Patterson Air Force Base, Ohio
Gail DiSalvo, Ciba-Geigy Corporation
Joseph F. Dolowy, Jr., DWA Composite Specialties, Inc.
Thomas F. Foltz, AVCO Corporation
J. David Forest, Ferro Corporation
Amit Ghosh, Rockwell International Science Center
Hugh H. Gibbs, E. I. du Pont de Nemours and Company
David M. Goddard, Material Concepts, Inc.
Thomas B. Gurganus, Alcoa Technical Center
Terence F. W. Hall, Northrop Corporation, Aircraft Division
George E. Harris, McDonnell Douglas Corporation
Willard Hauth, Dow Corning Corporation
William Hettinger, Jr., Ashland Petroleum Company
Paul R. Hoffman, AVCO Corporation
Paul E. Hood, ARCO Metals Company
David W. Johnson, LTV Aerospace and Defense Company
Brian H. Jones, Compositek Engineering Corporation
Ronald Kollmansberger, Fairchild Republic
John Mahon, Grumman Aerospace Corporation
Warren Marx, Grumman Aerospace Corporation
E. Lee McKague, General Dynamics Corporation
Raymond J. Palmer, Douglas Aircraft Company
Jerry Persh, OUSDR&E, The Pentagon
Paul F. Pirrung, Wright-Patterson Air Force Base, Ohio
Leonard Poveromo, Grumman Aerospace Corporation
Karl M. Prewo, United Technologies Research Center
John R. Roquemore, Lockheed-Georgia Company
Thomas E. Schmid, Pratt & Whitney
David L. Smith, McDonnell Aircraft Company
Donald G. Spinks, McDonnell Aircraft Company
Thomas E. Steelman, Rockwell International
Robert J. Stout, General Dynamics Corporation
Allan T. Taylor, Boeing Commercial Airplane Company
Albert H. von der Esch, Boeing Military Airplane Company
Brian A. Wilson, Aerojet Strategic Propulsion Company
Carl H. Zweben, General Electric Company

Workshop 3 Attendees

Norman R. Adsit, Rohr Industries
Robert E. Akans, Kaiser Aluminum
Sam C. Aker, Murdock Engineering Company
Lewis R. Aronin, U.S. Army Materials and Mechanics Research Center
Stanley M. Barkin, National Research Council
James E. Bell, Martin Marietta Corporation
Christopher B. Benham, Emerson and Cuming, Inc.
William P. Benjamin, Northrop Advanced Systems Division
Harold Berger, Industrial Quality, Inc.
Charles E. Bersch, Institute for Defense Analyses
Robert Biornstad, Martin Marietta Aerospace
Gregg L. Bouslog, TRW
Richard G. Brown, Atlantic Research Corporation
Alvin Ray Cederberg, Brunswick Corporation
Henry Chess, Xerkon Company
Roger B. Clough, National Bureau of Standards
Jack L. Cook, ARCO Chemical Company
William P. Couch, Martin Marietta Baltimore Aerospace
Michael A. DeCrescente, United Technologies Research Center
Thomas L. De Fazio, Charles Stark Draper Laboratory, Inc.
Jay Desai, General Electric Company
Russell Diefendorf, Rensselaer Polytechnic Institute
Richard J. Dionizio, Bonded Technology, Inc.
James Eaton, Cincinnati Milacron Company
John Fiore, Fairchild Industries Incorporated
Sidney I. Firstman, IIT Research Institute
Frank Frechette, Sohio Engineered Materials Company
Dana M. Granville, US Army Materials and Mechanics Research Center
Paul Harruff, McDonnell Douglas Astronautics Corporation
Randolph C. Helmink, Allison Gas Turbine
Jim Huang, Naval Air Development Center
F. K. Huber, Beech Aircraft Corporation
Joe D. Hudspeth, Murdock Engineering Company
Thomas G. Hynes, Composites Horizons, Inc.
Gary Jacaruso, United Technologies Corporation
Arthur M. James, Lockheed-California Company
Arnold H. Kahn, National Bureau of Standards
William J. Kearney, Atlantic Research Corporation
James J. Kelly, Office of Naval Technology, NAVMAT
Surya P. Kodali, Martin Marietta Company
Hans Kossler, Bell Helicopter Company
Joseph R. Lane, National Research Council
Richard J. Larsen, Goodyear Aerospace Corporation
A. T. Laskaris, AVCO Corporation
Rodney M. Linford, McDonnell Douglas Corporation
Charles P. Logan, Jr., HITCO
Thomas Luhman, Boeing Aerospace Company
Gerald A. Lunde, Rohr Industries
Bernard Maggin, National Research Council
P. H. Martin, Dow Chemical Company
Barbara Masi, Massachusetts Institute of Technology
Milan Maximovich, Lockeed Missiles and Space Company, Inc.

Lawrence E. McAllister, Allied/Bendix Aerospace Company
Joe Melill, Northrop Corporation
William K. Miller, General Motors Corporation
Soo-Ik Oh, Battelle Memorial Institute
Joseph E. Parnell, Alcoa Technical Center
Marina R. Pascucci, GTE Laboratories, Inc.
Arvid E. Pasto, GTE Laboratories, Inc.
Gerald Patterson, Atlantic Research Corporation
Milton J. Poullos, Jr., LTV Aerospace and Defense Company
David J. Raasch, Douglas Aircraft Company
S. Victor Radcliffe, National Forge Company
Edward Raymond, Cameron Iron Works
Darrell Reneker, Office of Science and Technology Policy, The White House
William M. Robertson, Gulf Stream Aerospace Corporation
Robert G. Rudness, Knoxville, Tennessee
Michael J. Salkind, Bolling Air Force Base, D.C.
S. C. Sanday, Naval Research Laboratory
Thomas S. Scarpati, United Technologies, Sikorsky Aircraft
Gerhardt F. Schenck, United Technologies, Pratt & Whitney
H. C. Schjelderup, Douglas Aircraft Corporation
Daisy O. Schrock, Wright-Patterson Air Force Base, Ohio
Charles L. Segal, Raleigh, North Carolina
Shabbir A. Shad, LTV Aerospace and Defense Company
James K. Spitler, Lockheed-Georgia Company
Kirby Stone, Cincinnati Milicron Company
William D. Timmons, Celanese Research Company
Bernhard R. Tittman, Rockwell International
Vincent J. Vitali, Pratt & Whitney Company
James A. Wedin, Xerkon Company
Les Wilshire, Vought Corporation
James S. Winegar, Fiber Technology Corporation
Robert Wolffe, E. I. du Pont de Nemours and Company
H. Thomas Yolken, National Bureau of Standards
Charles Zanis, Naval Sea Systems Command
Robert L. Zwart, Fairchild Republic

APPENDIX D

Acronyms

AFML	Air Force Materials Laboratory
AIMS	Automated Integrated Manufacturing Systems
ALPID	Analysis of Large Plastic Incremental Deformation
APLS	Automated Ply Lamination System
ATF	Advanced Tactical Fighter
BMI	Bismaleimide
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CAE	Computer-Aided Engineering
CAP	Consolidation by Atmospheric Pressure
CNC	Computer Numerical Control
CVI	Chemical Vapor Infiltration
DARPA	Defense Advanced Research Projects Agency
FAW	Fiber Areal Weight
FIA	Forging Industry Association
HIP	Hot Isostatic Pressing
LCF	Low Cycle Fatigue
NC	Numerically Controlled
NDE	Nondestructive Evaluation
PI	Polyimides
PM	Powder Metallurgy
PVA	Plan View Area
RF	Radio Frequency
RSP	Rapidly Solified Powder
SPF/DB	Superplastic Forming/Diffusion Bonding

END

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